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Evaluation of the Radial Flow Fluidized Filter (RFFF) and the Radial Reverse-Fluidized Filter (RFRF) Systems

By

Kevin Ke-Jong Liu

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements of the degree of Master of Science in Environmental Engineering

Department of Civil and Environmental Engineering

Edmonton, Alberta

Fall, 2003

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FACULTY OF GRADUATION STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitles EVALUATION OF THE RADIAL FLOW FLUIDIZED FILTER (RFFF) AND THE RADIAL REVERSE-FLUIDIZED FILTER (RFRF) SYSTEMS submitted by KEVIN KE-JONG LIU in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in ENVIRONMENTAL ENGINEERING.

Dr. Daniel W. Smith (Supervisor)

Dr. Mohamed Gamal El-Din

Dr. John Feddes

Date approved: September 29, 2003

ABSTRACT

An investigation of the applicability of Radial Flow Fluidized Filter (RFFF) and Radial Flow Reverse-Fluidized Filter (RFRF) unit in the removal of particulate matter in drinking water treatment has been implemented for 18 months. The filter performance and repeatable data presented in the result section show that removals of particles over >2μm on Mil-Spec 13 (40 to 90 μm), Mil-Spec 12 (50 to100 μm), and Mil-Spec 10 (90 to 150 μm) filter medias were greater than 97%, 95%, and 92%, respectively. In the filter challenge test *Bacillus subtilis* spores were chosen to feed to the filter and the log removals on Mil-Spec 13 and Mil-Spec 12 filter media were 1.54 and 1.13, respectively. Filter-aid polymer with dosage range of 2.2 to 4.4 mg/L was found effective to enhance filter performance on the raw water. More specifically, the unit was found to remove a substantial percentage of particles and offer low backwash water (0.3% to 3%) requirements.

This manuscript is dedicated to my mom and dad for always supporting me in my academic and life pursuits.

To my love, Linda Men-Tzu Liang, for continuously encouraging and inspiring me.

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ACRONMS

CFU	Colony Forming Units
counts/mL	Numbers of particles measured by particle count meter per millilitre
G	Mixing intensity (sec^{-1})
GPM	Flow rate, US gallons per minute
kPa	Pressure, Kilopascal
mg/L	Milligram per Litre
mL	Millilitre
m/hr	Flow rate, meter per hour
NTU	Nephelometric Turbidity Unit
psi	Pressure, pound per square inch
RPM	Revolution per minute
RFRF	Radial Reverse Fluidized Filter
RFFF	Radial Flow Fluidized Filter
µm	Micrometre
WTP	Water Treatment Plant

1. INTRODUCTION

1.1. Background

The Radial Flow Fluidized Filter (RFFF) has a broad range of application in manufacturing or process industries such as oil refinery, which require the removal of impurities or solids from an effluent. However, due to the nature of the filter media, conventional backwashing methodologies were ineffective; media were therefore either replaced or regenerated through external cleaning when filter performance deteriorates. Both the cost and complexity of this process restricted the competitiveness of the RFFF unit, as compared to sand filters in many filtration applications. After a backwash Ph.D. study done by Guzman (1997) at the University of Texas at Arlington, a second generation RFFF unit was invented by the John Martin Company, which could fluidize non-bonded media particles for filtering impurities from an influent, and then subsequently backwashed by dropping the media particles to free the impurities. This type of filter unit was tested by Baxter et al. (2001) at the University of Alberta and found to remove a substantial percentage of ISO A2 fine dust particles and offered low backwash water requirements. However, inconsistent results caused by improper systematic parts and ineffective backwashing methodologies. The parts problems were related to leakage, durability, and flexibility, and the backwashing problems involved incomplete cleaning of the screens and filter media. These problems led to the development of a redesigned third generation RFFF unit.

The third generation RFFF unit had two concentric perforated cylinders covered with specific screen material, which had the proper sieve opening to contain certain size of filter media between two cylinders. An additional annular space was placed around the outside cylinder to contain the flow during the filtration and backwashing. This also provided for a self-enclosed case if so desired, thus eliminating the need for an external filter case. Top and bottom head assembles, which had outlets to receive and discharge

water sources, were able to seal the two perforated cylinders and annular space to form a completely sealed RFFF unit. The porous media was composed of tiny glass spheres which were of uniform size for a particular filter but can range widely in size for different filters. The spheres can be as small as powder and as large as coarse sand.

1.2. Objectives and Research Plan

The main objectives of this study were to confirm and expand upon the results concerning unit performance generated in the preliminary study, and to determine the feasibility of applying the RFFF technology to the treatment of different source waters for particle and organics removal. The second objective was to conduct a series of challenge tests, and on-site evaluation of unit performance in the areas of drinking water treatment, drinking water pre-treatment, and particulate removal from run-off. Note that the delay on the laboratory-based testing was attributed to the ongoing filter innovation process. Details can be found in the preliminary result and discussion sections.

1.2.1. Confirmation and Expansion of Preliminary Results

In order to ensure that the results obtained from the preliminary investigation were valid over a wide range of operating conditions, a series of laboratory-based pilot tests were conducted. The tests confirmed and expanded upon those previously performed and allowed for a quantitative evaluation of the effects of a number of factors on unit performance including:

- media size;
- screen type and screen sieve size;
- unit flow rate; and

- particle loading.

The redesigned unit was evaluated with respect to particulate removal and backwash efficiency. Performance was monitored using online turbidity meters and particle counters. The result of the pilot testing was used both to determine the need for design modification, as well as to establish the most efficient operational conditions for the RFFF unit during on-site analyses.

1.2.2. Use of Filter-Aid Polymer

In order to increase the size of filterable particles, as well as to form easier-to-filter particle agglomerates. Filter-aid agents such as polymers are added to the water. The effect of a few polymeric aids was evaluated to improve the RFFF unit's performance in terms of increased particle removals and shortened ripening time. Since there were thousands of polymers products in the market, searching for the optimal one for the RFFF unit with each raw water was not possible due to limited time and resources. However, Simon Thomas, project engineer in EPCOR, identified PERCOL LT-7996 as filter-aid polymer which was found to work well for EPCOR's deep bed sand filters. As a result, PERCOL LT-7996 was used as a bench-scale testing agent to evaluate the effect of polymer addition in the RFFF unit.

1.2.3. Filter Challenge Test

The true measure of filter performance in the drinking water treatment industry was the filter's ability to remove pathogenic organisms such as *Giardia lamblia* and *Cryptosporidium parvum*. Experiments involving such organisms were costly and require the ability to contain and decontaminate all filter effluent. Recent studies have concluded that some aerobic bacterial spores such as *Bacillus subtilis* can serve

as surrogates in the determination of physical removal of microbiological contaminants. The spores were ellipsoidal to spherical in shape and on average measure approximately 0.5 x 1.0 x 2.0 μm (Rice et al., 1996), which sizes were smaller than those of *Giardia lamblia* and *Cryptosporidium parvum*; therefore, if the RFFF unit was capable of removing *B. subtilis* spores physically, if would be expected to produce similar reduction of pathogenic organisms. As such, the ability of the RFFF unit to remove microorganisms was evaluated using *B. subtilis* spores, which were robust, easy to handle, cultured in large quantities, and easily identified.

1.2.4. On-site Evaluations

The last phase of the RFFF project was intended to perform experiment test using the best available design under the most efficient and effective operating conditions.

The first on-site evaluation involved the filtration of clarifier effluent water from the E.L. Smith Water Treatment Plant. This source water had relatively similar particle distribution characteristics to that used in the laboratory pilot testing because particles of destabilization would be similar to the zero charge ISO A2 fine dust. Filter performance was monitored through online turbidity and particle count measurements.

1.3. Hypothesis

The following hypothesises were proposed;

1. The revised Radial Flow Fluidized Filter (RFFF) could achieve the same or better performance over the previous results reported by Baxter et al. (2001);
2. that a relationship exists between particle removal from simulated water using ISO A2 fine dust and particle removal from natural surface water and clarified water;
3. that particle destabilization with filter-aid chemicals significantly improves filter's performance in terms of particle removal efficiency;
4. that the radial flow filter requires a small amount of backwash water for cleaning; and to bring filter back to filtration cycle; and
5. that the radial flow filter can achieve the same or better log pathogen reduction as conventional rapid sand filters.

2. LITERATURE REVIEW

Filtration is a unit operation in which the particles are removed from water by being blocked on the surface of the medium or being collected throughout its depth as water passes through a filter. Without the use of filter-aid chemicals such as polymers, the removing mechanisms of particles are simply based on physical straining and non-straining processes. The removing mechanisms of particles include various chemical and physical interactions and particle transport processes when filter-aid chemicals were used.

First, the types of particles to be removed during the water treatment processes and some of their properties are described. The review of fundamental aspects of filtration in terms of mechanisms of removal at particles from water as it flows through the RFFF unit. Those are very similar to the mechanisms occur in conventional porous filters even thought the flow patterns are different. Then, an overview is presented of the application of *Bacillus subtilis* spores as a microbial surrogate for a variety of pathogens. Finally, a review of the characteristics of polymers as filter-aid agent and the factors affecting the polymer performance were presented.

2.1. Particles in Water

Particles were defined as finely divided solids larger than molecules but generally not distinguishable by the unaided eye (Montgomery, 1985). In natural water, particles vary widely in origin, concentration and size. It was believed that they principally come from land-based or atmospheric sources, and chemical and biological processes (AWWA, 1990). For example, clay and pathogenic organisms are constituents of land-based and atmospheric sources. Algae and aquatic organic detritus were produced by chemical and biological processes. However, some water treatment processes, notably coagulation and softening, can also produce other insoluble chemical products.

The charge, floc size and density were the most important characteristics of particles in filtration. Because of their small size, particles are usually electrically charged, either through adsorption of ions on their surface, ionization of the particles, or both. In natural waters, particles usually carry a negative surface charge in the neutral pH range. Because of the surface charge, the particles move toward the opposite electrode when an electrical potential is applied across a suspension. Thus, the charge of particles can be quantitatively measured by the potential that causes the motion of the particles. This potential is called zeta potential (ZP) or electrokinetic potential. The pH and ionic strength of water are two major factors which affect the ZP value. In natural waters the ZP of clay particles ranges from -12 to -25 mV (Shull, 1967). It should be realized that a colloidal system as a whole does not have a net electrical charge, and the primary charge on the particle must be counterbalanced. This was significant in explaining the stability of some colloidal suspensions by the electric double layer theory (Stumm and Morgan, 1981).

A better understanding of the physical and chemical properties of particles in water would give an insight into the dominant mechanisms of water filtration and provide a guideline for improving the filtration efficiency. When particle size is greater than the pore opening of filter media, straining is considered the possible removing mechanism. When particle sizes are smaller than the pore opening, the particles are collected inside the filter bed, and other mechanisms are involved. Yao et al. (1971) found that there exists a critical size of about 1 μm for which the transport efficiency was minimum. For smaller particles, diffusion plays an increasing role, and for larger particles, sedimentation becomes dominant. It has been noted that when the particles and filter media carry a similar charge, the filter removal efficiency was reduced as compared to particles carrying different charges (Ghosh et al., 1975). Some researchers (Boyd and Ghosb, 1974 and Shull, 1967) also found that when the ZP of a particle was close to zero on the negative side, the removal efficiency reaches optimum.

2.2. Modes of Filter Operation

There are two primary methods of operating filters: constant-rate filtration and declining rate filtration. Those two methods differ mainly in the way the filtration driving force is controlled across the filter. The concepts of constant-rate filtration and declining-rate filtration were described by Cornwell et al. (1984). For the RFFF unit, both operations are possible depending on the type of operating system and the pumps used.

A number of advantages have been observed with the declining rate filtration as compared to the constant rate filtration. Baylis (1959) reported on the results from an experimental filtration plant at Chicago, where no rate controllers were used on some filters. The filtration rate was allowed to decline from a maximum value at the beginning of the run when the media was clean to minimum value when the filter was ready for backwash. It was concluded the effluent quality under variable filtration rate was neither worse nor better than that produced at constant rate, but total water production was higher. The results of similar tests of declining-rate filtration conducted by Hudson (1959) at Wyandotte, Michigan. water treatment plant confirmed that a longer filter run was achieved. In addition, the study showed that better quality water was produced by the declining-rate filter than by the conventional constant-rate filter.

From the system design point of view, declining-rate filtration does not require a dedicated pump, which can overcome the pressure increase (headloss) of the system to provide constant flow rate into the filtration system. Instead, a relatively cheap centrifugal pump, 3-phase 230 V, was preferred for the RFFF project, which can provide the desired maximum flow rate initially and gradually decreased flow rate at the end of filtration run.

2.3. Mechanisms of Filtration

The mechanisms of particle removal from liquid during filtration are complicated. Since RFFF unit uses granular same sized glass beads as filter media, the mechanisms are assumed similarly to the granular mono sand filter in three steps: transport, attachment and detachment (Amirtharajah, 1988), as illustrated in Figure 1. However, due to the differences of filter media size, thickness of filter bed, and flow patterns, these three mechanisms are only considered to be the potential mechanisms on radial flow filter units.

For the RFFF system the water flow comes from two directions, namely radial and axial flow, and the final flow direction was a flow balance of the two directions. However, due to lack of hydrodynamic analysis of the RFFF system, the flow direction somewhere in the angle between zero to 90 degree horizontally depending on such factors as flowrate, media size, etc., as shown in Figure 2.

The removal of particles within the pores of a filter was first mediated by transport mechanisms that carry the small particles close to the filter grain surfaces. The filter grains were also called collectors. When the particles were very close to the collectors, surface forces might cause capture of the particle and its attachment to the collector. As particles were removed on the filter grains, they tend to accumulate in a variety of geometric configurations. These configurations were related not only to the filter grains but also to particles that were previously removed and were now acting as additional collectors. Some common configurations were spherical caps on the tops of grains and tubular structures within the pores. If the overall superficial filtration rate remains constant, then the fluid velocities would result in increasing drag forces on the deposited particles, and when the drag forces exceed the adhesive forces, particles were detached and reach lower depths within the filter. Alternatively, the detachment might be discerned as the avalanche effect of arriving particles. Thus, in a filter layer that has reached a saturated but metastable configuration of deposited particles, the mechanisms of attachment and detachment might occur simultaneously.

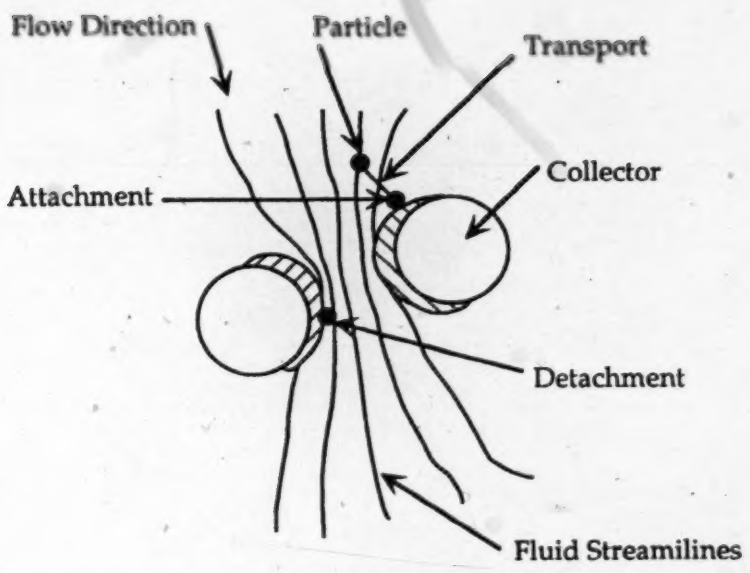


Figure 1. Mechanisms of Filtration.
(adapted and modified from Amirtharajah, 1988).

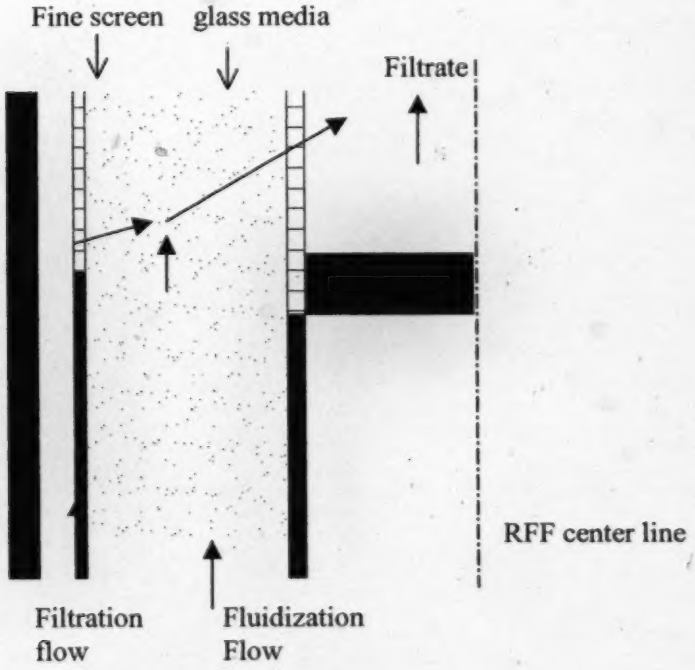


Figure 2. Flow direction patterns of the RFFF.

The transport of particles in the pores of the media was the combined effects of physical and hydrodynamic processes including diffusion, sedimentation, interception, inertia and hydrodynamic action. It was generally accepted that under the conditions of water filtration the dominant mechanisms were diffusion, sedimentation and interception (Habibian and O'Melia, 1975). Diffusion was the transport resulting from random Brownian motion from bombardment of the particle by molecules of water. It was obvious that particle motion by this mechanism was stochastic in nature and would become increasingly important for particles <1 μm in size. Sedimentation was due to the force of gravity and the associated settling velocity of the particle, which cause it to cross streamlines and reach the collector. For this mechanism, particle and fluid densities and viscosity play important roles. It becomes increasingly important for particles > 1 μm. Interception occurs when particle motion along a streamline was sufficiently close to the collector for attachment to occur. For large particles of low density, interception and sedimentation were about equally important in controlling particles removal. As the density of the particles increases, sedimentation becomes controlling (Amirtharajah, 1988).

The attachment mechanism involved either electrostatic interactions, van der Waals forces, or surface chemical interactions (O'Melia and Stumm, 1967). Attachment was affected by both physical and chemical factors. There were two models which were used to describe the mechanism (Adin and Rebhun, 1974). The "double-layer model" was based on an interaction between the electrostatic repulsive forces and van der Waals forces. The "bridging model" explains effects that were not treated by the first model as resulting from chemical bonding and bridging of the suspension particles through reaction with the flocculants. It has been shown both theoretically and experimentally that particle capture would be favourable when surface charges of the particles and media were of opposite sign. Where the media surface was covered by deposited particles, the collection was effective only if the particles have been adequately destabilized. O'Melia and Stumm (1967) suggested that these

conditions were exactly analogous to coagulation.

The detachment mechanisms include scour due to increased interstitial velocity gradients in the bed or as a result of floc shearing. Its magnitude would depend on the influent concentration, the length of filter run, the hydrodynamic forces and deposit morphology. Only until recently had quantitative description of the detachment mechanisms been developed by Adin and Rebhun (Ginn et al., 1992). It should be noted that the mechanisms of attachment and detachment might occur simultaneously and the detachment mechanisms often control the effluent particle concentration and particle size distribution as the significant portion of particles in the effluent come from the detached flocs (Ginn et al., 1992). Table 1 summarizes the important transport and attachment mechanisms and shows the predicted functions of initial filter coefficient as the variations in diameter of particles d_p, approach flow velocity V_o, and zeta potential ξ_o. Table 2 summarizes the qualitative effects of increasing each of process parameters on the particle removal efficiency.

It should be noted that the most significant achievement made previously was the better understanding of relative significance of various processes involved on the removal efficiency of particles. Adin and Rebhun (1974) stated that the transport mechanism appears to be sufficient to accomplish their task even for the most difficult to transport particles. Thus, the transport mechanism was relatively insignificant in filter design. On other hand, the control of filtration should be directed to improve attachment efficiency, mainly through the selection of medium, and the use of polymers as filtration aids.

Table 1. Summary of transport and attachment mechanisms and their dependence on operating Conditions.

Mechanisms	λ_o		
	d_p	V_o	ξ_o
Straining	$d_p^{3/2}$	*	*
Gravity Settling	d_p^2	V_o^{-1}	*
Interception	d_p^2	*	*
Brownian Diffusion	$d_p^{-3/2}$	$V_o^{-2/3}$	*
Electrostatic Force	d_p^{-1}	V_o^{-1}	ξ_o^{-1}
London Forces	d_p^2	weak	weak

* No predicted dependence. (adapted from Boyd and Ghosh, 1974).

Table 2. Effects of different parameters on particle efficiency

Parameter	Change in Parameter	Removal Efficiency
Influent particle concentration	Increase	No change
Particle density	Increase	Increase
Interstitial velocity (filtration rate)	Increase	Decrease
Filter pore diameter (medium grain diameter)	Increase	Decrease
Length of the filter pore (depth of the medium)	Increase	Increase
Particle attachment efficiency (degree of destabilization)	Increase	Increase

(adapted from Letterman, 1987)

2.4. Operating Pressure Increase

The pressure drop (i. e., headloss) was a common terminology in filtration that always occurs when water flows through the filter media. It was recognized as early as in the 1900's that this pressure drop was attributed to the combined effects of the drag friction at the surface of the media and the continuous contraction and expansion of the fluid as it passes through pore openings in the filter. The RFFF has the same phenomenon, but the pressure drop across surface layer of filter results the increased pressure on the mainstream of filter influent water, from which the pressure was measured. This is called "pressure increase" since it is measured upstream of the filter.

If straining was the controlling mechanism, the particles might form a layer of deposit on the surface of the filter medium. The pressure increase of the mainstream depends on the size distribution and mechanical properties of the filtered particles.

The development of pressure increase in the RFFF was complicated. Its rate depends on the rate of particle volume removal, the filtration rate, and the size and total volume of the interstitial spaces. The lowest rates of development of pressure increase and the longest filter runs were obtained when the region in which deposition takes place was deep (' ng pore lengths) and the mean grain size was large (large pore diameters). The development of pressure was minimized by effective utilization of all the void space in the bed. Low filtration rates also tend to yield low rates of pressure increase development. For a given mass concentration of particles, increasing particle density decreases the volume of interstitial void space consumed in the deposition process and therefore decreases the rate of development of headloss (Letterman, 1987).

Table 3. The Effects of increasing certain parameters on headloss

Parameter	Change in Parameter	Change in Rate of Development of Pressure increase
Rate of particle deposition (mass basis)	Increase	Increase
Filtration rate	Increase	Increase
Filter pore diameter (medium grain diameter)	Increase	Decrease
Length of the filter pore (depth of the medium)	Increase	Decrease
Depth of the medium over which there was deposition	Increase	Decrease

(adapted from Letterman, 1987)

2.5. Filter Ripening and Initial Degradation of Filter Effluent

The filter ripening happens during the period which the backwashed filter's initial effluent particle count and turbidity were higher than the average effluent standards. During this period, the filtrate has been observed to deteriorate for a few minutes and then improve over about 30 minutes before reaching the best level of the entire run (AWWA, 1990).

A number of studies have been reported in the literature for investigating the initial degradation of filter effluent. Amirtharajah and Westein (1980) first showed that the initial effluent quality from a repeatedly used filter could be divided into three stages: the lag period, the rising limb culminating in two turbidity peaks and the long receding limb. They proposed that the lag period was due to the clear backwash water remaining in the underdrain system up to the bottom of the filter media, that the rising limb was due to particles detached during collisions of settling media at the end of the backwash, particles from the backwash water and also the agitation in the collection and clear well channel, and that the receding limb was due to the dispersion and mixing of the media-derived particles from the filter with the influent and the accumulation of

influent particles within the media pores. In the RFFF unit, the last two stages stated above do seem to happen while the first lag period doesn't apply due to no underdrain system involved

Francois and Van Haute (1985) described the filter ripening phase, modifying Amirtharajah and Westein's theory. They indicated the initial degradation in quality was composed of 95 percent of particles from the influent water and 5 percent of particles from the backwash remnant water.

2.6. Reducing Bushing Injection Point

In order to have a negative pressure from injection point to improve either ISO A2 fine dust, polymer, or spore introduction to the RFFF unit, a reducing bushing was needed in either prior to or after the centrifuge pump. The simple equation (Bernoulli, 1738) can be found as follows:

$$\frac{P_1}{\rho_1} + gZ_1 + \frac{V_1^2}{2} = \frac{P_2}{\rho_2} + gZ_2 + \frac{V_2^2}{2} = \text{constant} \quad \text{Equation 1.}$$

Since water liquid was considered uncompressible in standard condition, then liquid density $\rho_1=\rho_2$, so when cross section area was decreased by narrowing the diameter, velocity (V_2) increases so that the pressure (P_2) was less than P_1 (assuming a equal-level stream, in which $Z_1=Z_2$).

2.7. Pretreatment and Direct Filtration

The objective of pretreatment was to facilitate a given liquid-solid separation process, which might be achieved by adjusting the nature of the feed material. Such adjustments

might be made intentionally according to a predetermined program or might occur indirectly as a result of previous process operations or handling techniques. Thus it can be examined separately but must not be viewed in isolation from the overall process operation.

Regarding a basic expression of filtration as,

$$\frac{1}{A}\frac{dV}{dt} = \frac{Q}{A} = \frac{P}{uR} \qquad \text{Equation 2.}$$

where

A was the surface face of the filter
V was the cumulative volume of filtrate collected up to any moment in time
t was the time lapse from commencement of filtration P was the operating pressure
μ was the viscosity of the feed system
R was the total resistance to filtration
Q was the rate of filtration

It was apparent that the rate of filtration was improved, and the separation was thereby made easier, by reductions in the factors μ and R, namely viscosity and resistance. Pretreatment, therefore, was confined to any changes which effectively reduce viscosity and resistance or increase solids concentration in the feed.

From preliminary results performed by Baxter et al. (2001), the RFFF required a period of ripening time to achieve the best particle removal efficiency. The ripening period could be shortened by either increased particle loading rate or increased filtration rate or both. With these increased rates, concerns have been raised whether the excellent quality of treated water can be maintained. To address these concerns, an extensive literature review has shown that two common approaches that might be directed to improve the performance of the RFFF: 1) modifying the pretreatment techniques so that most particles can be destabilized and settled in the upstream sedimentation basin; and 2) changing the surface properties and sizes of particles entering the filter to enhance both transport and attachment mechanisms. The former approach can be done

when clarified water from the E.L. Smith WTP was generally well destabilized and settled. The latter one can be achieved by dosing polymer as filter-aid agent.

The proper use of polymers as filter-aid agent not only maximizes the removal of particulate matter, but can also lead to improvement in a variety of other water quality parameters which were characterized by less conventional parameters (Dentel, 1991). This is done when naturally suspended particles representing a transport mechanism for undesirable organic and inorganic contaminants, taste, and odour resulting compounds, colour chemicals, and potential diseases can be minimized by filtration. For example, the increased concerns of pathogens, particularly *Giardia* spp. *and Cryptosporidium* spp., were extremely resistant to conventional disinfectant doses and contact times as in the cyst form. They, however, can be removed by proper filtration. As a result, effective filtration has been stressed as an essential requirement for conventional disinfection by a committee of the American Water Works Association (Craun, 1988).

Direct filtration is a surface water treatment process that includes additional of coagulant, rapid mixing, flocculation, and filtration. In this study, the flocculation tank was omitted and the process was referred to as in-line filtration, with flocculation occurring in the filter itself. The goal of adding polymer into the RFFF unit was to form pinpoint-sized floc that was filterable, rather than a large settleable floc formed by alum for example. The advantages and disadvantages of direct filtration were listed below:

The advantages:

1. capital costs were lower because no sedimentation was required;
2. chemical costs were lower because lower coagulant dosages were used;
3. lower sludge production accompanies with lower chemical dosages; and
4. operational costs were lower because less maintenance and power were required.

The disadvantages:

1. direct filtration cannot handle waters that were high in turbidity and/or colour;
2. less response time was available for direct filtration; and
3. less detention time was available for controlling seasonal tastes and odors.

The determination of the optimum coagulant dosage for direct filtration was selected by shutting-off the polymer feed for a few minutes instead of using Jar tests. This was done because small pinpoint floc was preferred for direct filtration. If the filtrate improved momentarily, the prior dosage was considered excessive. If the filtrate deteriorates immediately, the prior dose was at or below optimum. This was especially practical when using cationic polymer alone as a primary coagulant (Cleasby et al., 1984).

A number of studies have reported successful use of alum and cationic polymers simultaneously (Cleasby et al., 1984; Monscvitz et al., 1978). The objective in this phase was to compare the RFFF unit and plant's deep-bed filters. Only cationic polymer was added to the RFFF unit as a filter-aid agent because the E.L. Smith WTP only apply filter polymer along for their dual media deep-bed sand filters. However, during unusual spring runoff days when turbidity was above 100 NTU and particle was over 20,000 counts/mL for examples, the E.L. Smith WTP does add low dosage of alum (i.e. 1 mg/L) prior to the filter-aid polymer injection point.

2.8. Mechanisms of Polymer and Particle Interaction

It was well accepted that the mechanisms of polymer-particle interactions were considered similar to the coagulants used in the coagulation-flocculation process. For example, the overall rate of coagulation process was evaluated by determining the rate at which collisions occur between particles by fluid motion and by Brownian diffusion, multiplied by a "collision efficiency factor" which reflects the ability of chemical coagulants to destabilize colloidal particles and thereby permit attachment when

contact occurs.

Edzwald (1983) published figures of the six reactions of representation of the bridging model. The remainder of the polymer-particle complex with the polymer as a bridge (Reaction 1 and 2). If a second colloidal particle was unavailable, the extended polymer chain would eventually adsorb on other sites on the original particle, and the polymer would no longer be available to serve as a bridge (Reaction 3). The degree to which particle destabilization and aggregation occur was a function of polymer dose. High polymer dosage can saturate the colloidal surface, leaving no available reactive sites on the colloid thus producing a restabilized colloid (Reaction 4). Low polymer dose results in partial destabilization of the colloidal dispersion, leaving reactive sites available on the colloids but no polymer chains available for bridging. Finally, a system which has been destabilized and aggregated can be restabilized by prolonged agitation. By extending or intensifying agitation, the polymer-surface bonds can be broken allowing extended polymer segments to fold back onto the surface of the particles (Reactions 5 and 6).

The charge neutralization occurs when the particle destabilization was accomplished by adsorption of oppositely charged polymers on particle surfaces. The principles of this mechanism have been known for around thirty years. It has been postulated that the polymer assumes a flat configuration on the colloidal surface, rather than a configuration with many segments extending into the solution. An excellent modified charge neutralization model, patch model, used to describe the adsorption of relatively low molecular weight cationic polymers on negatively charged particles was proposed by Gregory (1973). Edzwald (1983) also showed the situation of polymer molecules adsorbed in a flat planar configuration. The polymer was assumed to adsorb in a small patch on the surface of the colloid. The resulting pattern on the colloidal surface consists of small patches of high-density positive charge surrounded by a sea of lower density negative charge. The particles flocculate as the positive patches bond to the negative surface of a colliding particle. In recent years, this model has been used increasingly to explain the flocculation behaviour of colloids when strong polymers

carrying the opposite charge were used.

2.9. *Bacillus subtilis* Spores as a Microbial Surrogate

2.9.1. Background of Water Treatment Challenge

The drinking water industry is undergoing a major paradigm shift due to increasing concerns over the potential of pathogens and disinfection by-products being present in drinking waters. As early as the 1970s, several outbreaks of illness caused by protozoan cysts and oocysts in drinking water have been witnessed. These cysts and oocysts, especially *Giardia lamblia and Cryptosporidium parvum,* are highly resistant to disinfectants (Daniel et al. 1993; Hoff et al. 1985) and were poorly correlated with traditional microbial indicators (Payment and Franco 1993; Chauret et al. 1995), making the traditional coliform group unsuitable for the prediction of the presence of protozoan parasites. In 1991 and 1992 alone, 34 outbreaks affecting 17,000 people were reported in the United States (Moore et al. 1994). It should be noticed that most of the outbreaks were observed in situations where drinking water quality standards were respected. As a result, it has become clear that current continuous process optimization based only on the practices of turbidity and particle count monitoring of treated water needs to be reevaluated.

Proposed guidelines for *Cryptosporidium* spp. *and Giardia* spp. are based on a maximum annual infection risk of 10^{-4} ($2.5x10^{-5}$/L and $5.5x10^{-6}$/L, respectively; VROM, 1995). Monitoring those low concentration microbial pathogenic contaminants presents a special challenge. Sampling and analytical methods that were available to detect *Giardia* spp. *and Cryptosporidium* spp. were not sensitive and not accurate. The time required for analyses does not allow for the practical use of the results in process control. Lack of real-time measurements of pathogens in water prevents utilities from being able to react to source water quality changes and

pro-active treatment optimization. Besides, cyst detection was expensive, technically complex, and hard to reproduce (Clancy et al. 1994). In the absence of quick and reliable analytical methods for pathogens, pathogens indicator must be used.

Concentrations of traditional bacterial indicators such as coliform bacteria, used as general indicators of fecal pollution, have shown significant correlations with parasite density in source water (Lechevallier and Norton 1992). This correlation, however, does not extend to finished drinking water. As particle counting and turbidity measurements were two of the most valuable water quality parameters used in assessing treatment plant performance, a comparison of source water and filtered water using these procedures has been proposed as a reliable method for determining treatment plant performance (Bellamy 1993). Turbidity appears to be an adequate predictor of the removal of cyst-sized particles when turbidity of source water was greater than 5 NTU; in less turbidity raw water sources, however, particle counting appears to be a more reliable indicator (Bellamy 1993). Not only did the recent waterborne outbreaks in the US occur at times when the turbidity was within regulatory limits, but research data showed that even at turbidity of less than 0.1 NTU, positive samples for *Cryptosporidium* spp. *and Giardia* spp. have been documented (McTigue 1995).

Spores from aerobic bacteria, mainly from the genus *Bacillus*, have been proposed as a surrogate for evaluating the effectiveness of the drinking water disinfection process (Kawamura et al. 1986; Toenniessen and Johnson 1970) because they were highly resistant to disinfection and do not pose a public health risk. *Bacillus subtilis* were present in large numbers in natural waters and their removal has proven to be well corrected with the removal of 3 to 6 μm particles (Rice et al. 1994). In an evaluation of an AWWA research sponsored study concluded the following benefits of aerobic spore analyses to water treatment plant operations (Nieminski 1998).

"Aerobic spores and particle counts can be used as surrogate measures to improve treatment plant performance. This type of microbial monitoring compliments the physical measurements of turbidity and particle count. Aerobic spores were

sufficiently plentiful in the majority of source water to allow removal calculations that would demonstrate from 3 to 4 log treatment efficiency. In contrast, only 1 to 3 log pathogen removal can be demonstrated based on natural occurrence of pathogens and their analytical sensitivity. Methods to perform aerobic spore analysis have been evaluated, modified, and simplified to be used by the water industry on a daily basis."

2.9.2. Biology of *Bacillus subtilis*

B. subtilis is a gram-positive, rod shaped, endospore forming bacterium (Kobayashi 1989). The ability to form resistant spores gives the species an advantage in surviving periods of dryness and nutrient deprivation. The spores have high resistance to chemical degradation, heat, radiating, UV light, and dry conditions (Kobayashi 1989). *B. subtilis* have a spore coat, cortex, and inner spore membrane surrounding the protoplast and they can remain dormant and viable for very long periods (Prescott et al. 1996). Sporulation is triggered when the organism is deprived of nutrients, usually carbon, nitrogen or phosphorus (Kobayashi 1989). Vegetative cells form ellipsoidal endospores in a complex developmental process lasting approximately 8 hours (Prescott et al. 1996).

Sporulation consists of seven distinct steps as seen in (Kobayashi 1989). Stage 0 is the vegetative cell. In stage I, axial filaments are formed within the vegetative cell. Stage II is characterized by the appearance of a septum dividing the cell into a large mother cell and a smaller prespore cell. In stage IIIa the mother cell engulfs the prespore and then the prespore becomes a spore protoplast or forespore in Stage IIIb. After this stage, the cell is committed to completion of the Sporulation and the process cannot be reversed even if environmental conditions become favorable again (Doi 1989). Stage IV sees the development of the cortex between the inner and outer forespore membrane. In stage V the spore coat is formed by deposition of proteins on the forespore membrane. The spore matures and becomes resistant to adverse environmental conditions in stage VI. In the final stage, Stage VII, the spore is

released from the mother cell. Endospores quickly germinate to form vegetative cells when in the presence of a germinant such glucose or L-alanine (Kobayashi 1989). The generation time of vegetative cells is approximately 0.43 hours at 40 °C in a nutrient rich medium (Prescott et al. 1996)

Endospore formation is most efficient when the vegetative cells have grown for at least six or seven generations in a nutrient rich medium before the onset of sporulation (Doi 1989). The spores can be detected by heating at 70 to 80 °C for 10 minutes and incubating on an appropriate growth medium. Only endospores and some thermophiles will survive this treatment (Prescott et al. 1996).

The benefits of using *B. subtilis* as a biodosimetric indicator are listed as follows:

1. the spores are highly resistant to environmental conditions;
2. the spores remain viable for long period of time;
3. the spores are non-pathogenic;
4. the spores do not reproduce in samples; and
5. very few other organisms existing in natural water will return a false positive in the enumeration of viable spores (Prescott et al. 1996).

2.10. Particle Counts and Turbidity

The concentration of particles in both total particle and selected size ranges has been discussed as a possible indicator of water quality and treatment efficiency. Particle counts can assess operational problems and determine water treatment efficiency (American Public Health Association, 1995). Particle counts may be useful in estimating the removal efficiency of *Giardia* spp. *and Cryptosporidium* spp. in filtrated water (LeChevallier and Norton, 1992). Although particle counting was more accurate, reliable, and reproducible than *Giardia* spp. *and Cryptosporidium* spp. counting, it has limitations such as variables (e.g. run time, sensor, flow rate of instrument, different sensor optics). The problem involved with instrument variability can be partially overcome by measuring percent removal over different size range through treatment instead of absolute particle concentrations. Some problems still exist (e.g. particle counts do not distinguish between living and nonliving particles, and between particles from untreated water and those formed during treatment processes. Plus, relation between particle removal and *Giardia* spp. *and Cryptosporidium* spp. removal was poor.

Turbidity is measured by detecting the scattered light by particles and has been used for many decades as an indicator of drinking water quality and as an indicator of the efficiency of drinking water coagulation and filtration process. Removal of turbidity should at least remove some degrees of pathogens in the water because pathogens usually were aggregated with particles in the source water. Turbidity provides no information about the nature of the particles because it was relatively crude measurement, detecting a wide variety of particles from a wide assortment of sources.

As a result, particle counts and turbidity measurement were both selected as indicators together by most of the water treatment plant. Studies from Cleasby et al. (1989) and similar data from Cullen and Letterman (1985) had found that if turbidity removal was low (e.g., 0.5 NTU), particle removal might be significantly higher (e.g., 2 log), and if particle removal was low, it was likely the turbidity removal would also be low by

calculating x-log removal values for turbidity (log T_0/T_e) and particle counts (log C_0/C_e). Note that T_0 and C_0 were the raw water values and T_e and C_e were the filtrated water values. This was because granular-bed filtration was efficient in removing particles in the size range measured by the particle-size analyzer but not as effective in removing smaller particles that scatter light and give high turbidity readings. These results tend to support the suggestion made by Beard and Tanaka (1977) and Tate and Trussell (1978) that filtration monitoring and control was enhanced when turbidity measurement was supplemented with particle count measurements.

3. FILTER CONCEPT DESCRIPTION

3.1. The RFFF Unit

The RFFF unit was supplied by the John Martin Company of Wichita Falls, Texas, and consists of two concentric perforated pipes, a porous media that fills the annular space between the pipes, and an acrylic-made cylindrical case to enclose the unit. Figure 3 shows the three essential cylindrical pipes, their aliments in the RFFF unit, and materials of each pipe or section of pipe.

The filter media consists of spherical glass beads of uniform size, classed according to U.S. Government Specification Mil-G-9954A, commonly referred to as Mil-Spec size screening. Four different media sizes, Mil-Spec 8, 10, 12, and 13 glass beads were received, which sizes were recommended by Baxter et al. (2000). The relationship between Mil-Spec sizing and bead diameter for the media used in this project was presented in the Table 4. Figure 4 shows the size of Mil-Sec 12 glass beads in SEM (Scanning Electron Microscope) through quality assurance. Each of the perforated pipes was covered with a screen with a nominal pore size of 20 to 105 μm, depending on the size of media, in order to contain the media without impeding the flow of water.

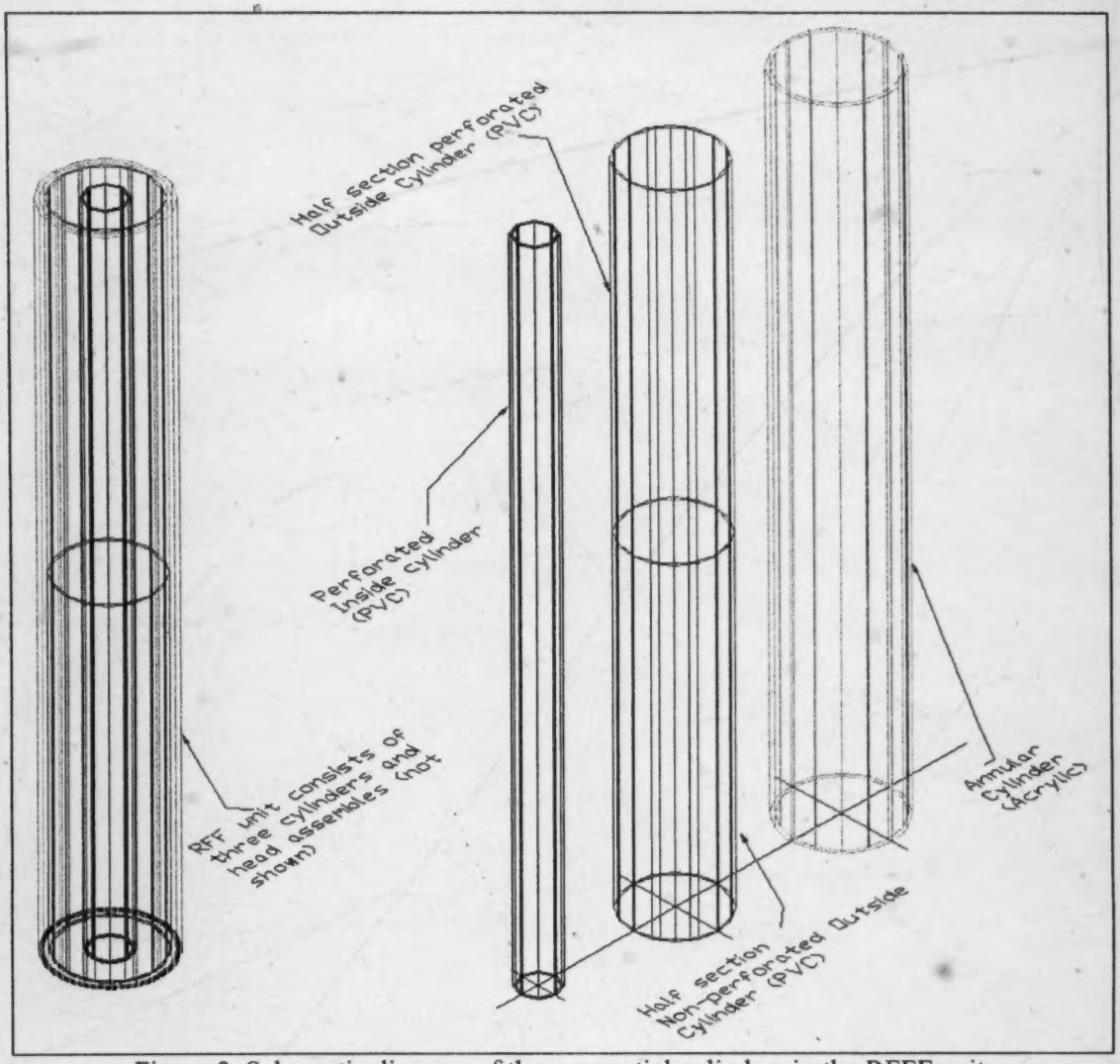

Half section perforated Outside Cylinder (PVC)
Perforated Inside Cylinder (PVC)
RFF unit consists of three cylinders and head assembles (not shown)
Annular Cylinder (Acrylic)
Half section Non-Perforated Outside Cylinder (PVC)

Figure 3. Schematic diagram of three essential cylinders in the RFFF unit.

Table 4. Relationship between Mil-Spec and bead size

Mil-Spec	Size Range (mm)
8	0.15 to 0.21
10	0.09 to 0.15
12	0.05 to 0.10
13	0.04 to 0.09

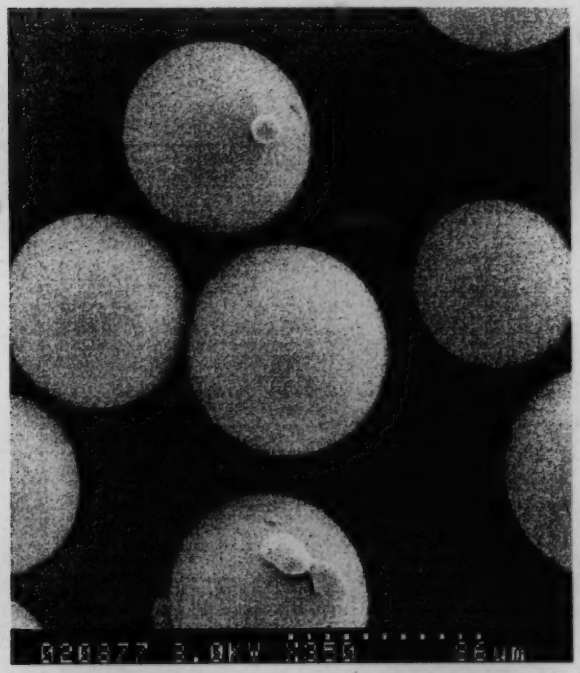


Figure 4. Mil-Spec 12 (0.05-0.10 mm) size glass bead in SEM (HITACHI S-2500).

3.2. Flow through the RFFF

The RFFF unit was designed to receive three separate influent flows, identified as fluidization water, filter influent water, and backwash water. The bottom head assembly seal with three cylinders via three o-rings, and a threaded cap and annular were encased. The bottom head assembly links the RFFF unit to the fluidization and filter influent flows. The filter influent water was the dirty water that was to be filtered. Both the fluidization water and the backwash water were from clean or treated water sources. During filtration, fluidization water was first introduced into the inner perforated pipe (Figure 5). The orifice inside the inner cylinder restricts flow within the pipe and the fluidization water enters the fluidization space between the two cylinders. The drag forces imparted from the fluidization water to the media cause the beads to be lifted upwards into the top of the filter in the annular space. Once the media has formed a packed bed in the top of the unit, filter influent water was introduced via the bottom head assembly into the both the annular space and the fluidization space. Flow from annular space and fluidization space was called radial and axial flow, respectively. Radial flow was the main direction of system filtration while axial flow provides small portion of filtration, but it also supports the fluidization of filter beads at the upper chamber. The radial fluid passes through the perforations in the outer cylinder, and then passes through the packed media and into the internal volume of the inner perforated cylinder. The filtered effluent then exits the unit through the top of the assembly (Figure 6). During backwashing, the filter influent and fluidization flows were closed, and backwash water was introduced through the top of the filter assembly (Figure 7). During the downward movement of the media, the beads were scrubbed through inter-bead contact as well as contact with the backwash water (Figure 8). Further, air scouring was applied at the bottom head to provide more rapid mixing to remove remaining particles; thereby removing previously trapped particulate matter. The particulate matter was carried out of the assembly with the backwash water via the inner perforated cylinder or fluidization water via the inner perforated cylinder and annular space.

Schematics of fluidization, filtration, and backwashing can been in Figure 9.

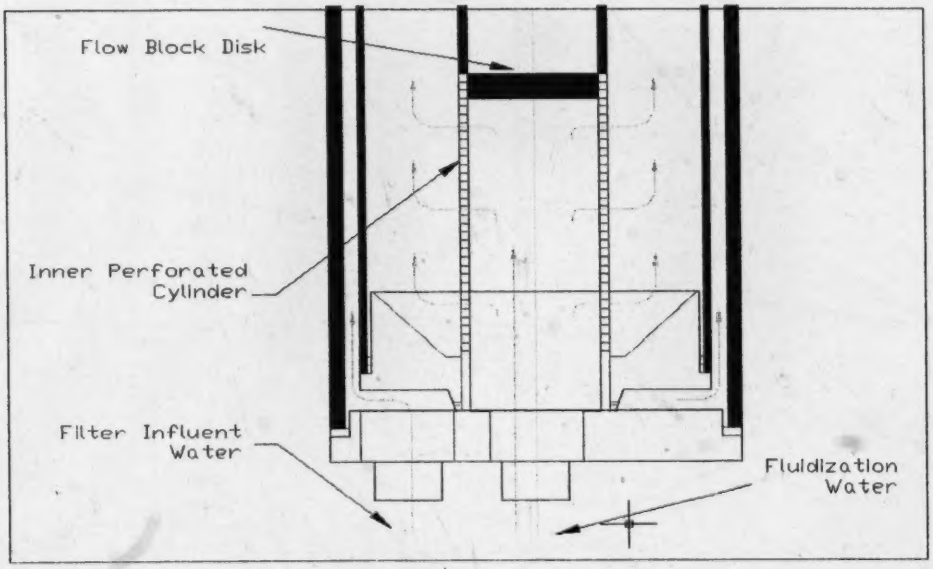


Figure 5. Flow through bottom head assemble during fluidization and filtration.

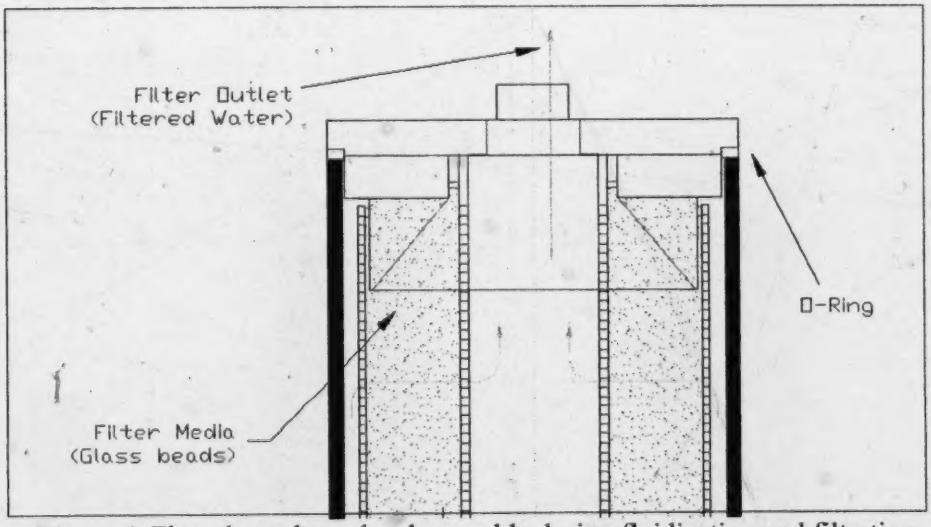


Figure 6. Flow through top head assemble during fluidization and filtration.

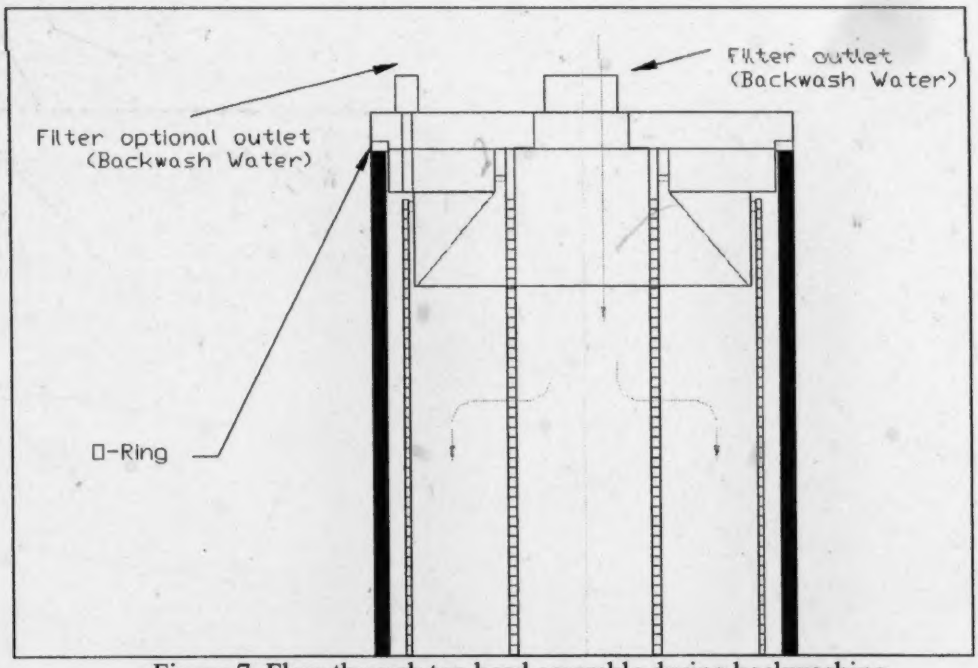


Figure 7. Flow through top head assemble during backwashing.

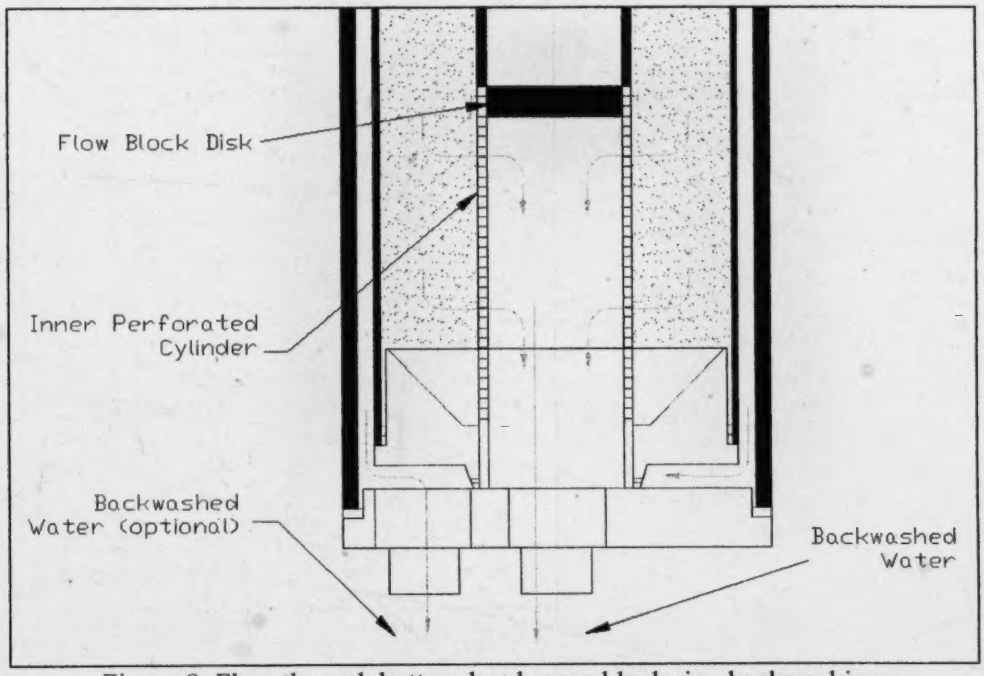


Figure 8. Flow through bottom head assemble during backwashing.

With respect to hydraulics of the experimental apparatus and accessibility of water source, municipal tap water was used as the backwash and fluidization water for the project. As would be discussed, the same water was also used in the preparation of the filter influent water solution. A constant supply of water to the system was guaranteed through the use of two 1000 L reservoirs. From the reservoir, water was delivered into the system via a 1.49 kW (2 hp), three-phase, and centrifuge pump. Piping between the various system components consists of rigid PVC pipe as well as flexible high-pressure tubing, both present in a variety of diameters, ranging from 6.4 mm (¼") I.D. for instrumentation lines to 25 mm (1") I.D. from the pump to the remainder of the system, and 38 mm (1.5") I.D. from the reservoirs to the pump.

3.3. Backwashing

After operation for a period of time, the RFFF unit, in terms of either available pressure drop or particle effluent count and turbidity limitation, was exhausted and needed backwash to renew its filter capacity. The aim of the backwash operation was to keep the filter acceptably clean, so that no progressive evidence of the development of dirty-filter problems, such as mud balls and filter cracks, occurred.

In RFFF unit, when the system flow was turned off all the glass beads in the upper chamber fell down to the lower chamber due to lack of fluidization flow. Large trapped and cake-form particles were flushed out from the bottom perforated cylinder of filter, followed with glass beads, while small particles tended to be suspended above of glass beads. Therefore, grey colour and light brown colour formed two distinctive layers at the lower chamber of filter, glass beads and suspended particles, respectively. The suspended particles were flushed out from the top perforated cylinder of filter as fluidization water introduced into the filter. The above complete operation was called one cycle of backwash. Three to five cycles were needed to keep the filter to an acceptably clean before return to filtration process.

In the RFRF unit, backwash cycle operation was very similar but reversed. Flow from the lower chamber was mixed and fluidized with the cake-formed particles and glass beads to the top chamber. During this time, impurities were flushed out from the top perforated inside cylinder and the lower perforated outside cylinder of filter. As the backwash flow turned off, relatively heavy particles and glass beads fell to the lower chamber while lighter particles tended to fall on the second layer in the lower chamber.

Number of backwash cycles depends on what kind of water was filtrated and the combined issues of screen and glass bead (e.g. type and size of screen, and size of glass beads). Through the test process, it was found that smaller sieve screens matched with smaller glass beads result in tighter cake formation in between screen and surface of glass beads. Therefore, the number of backwash cycles increased, and in some cases, backwashes failed to bring the RFFF unit back to the performance level required for operation.

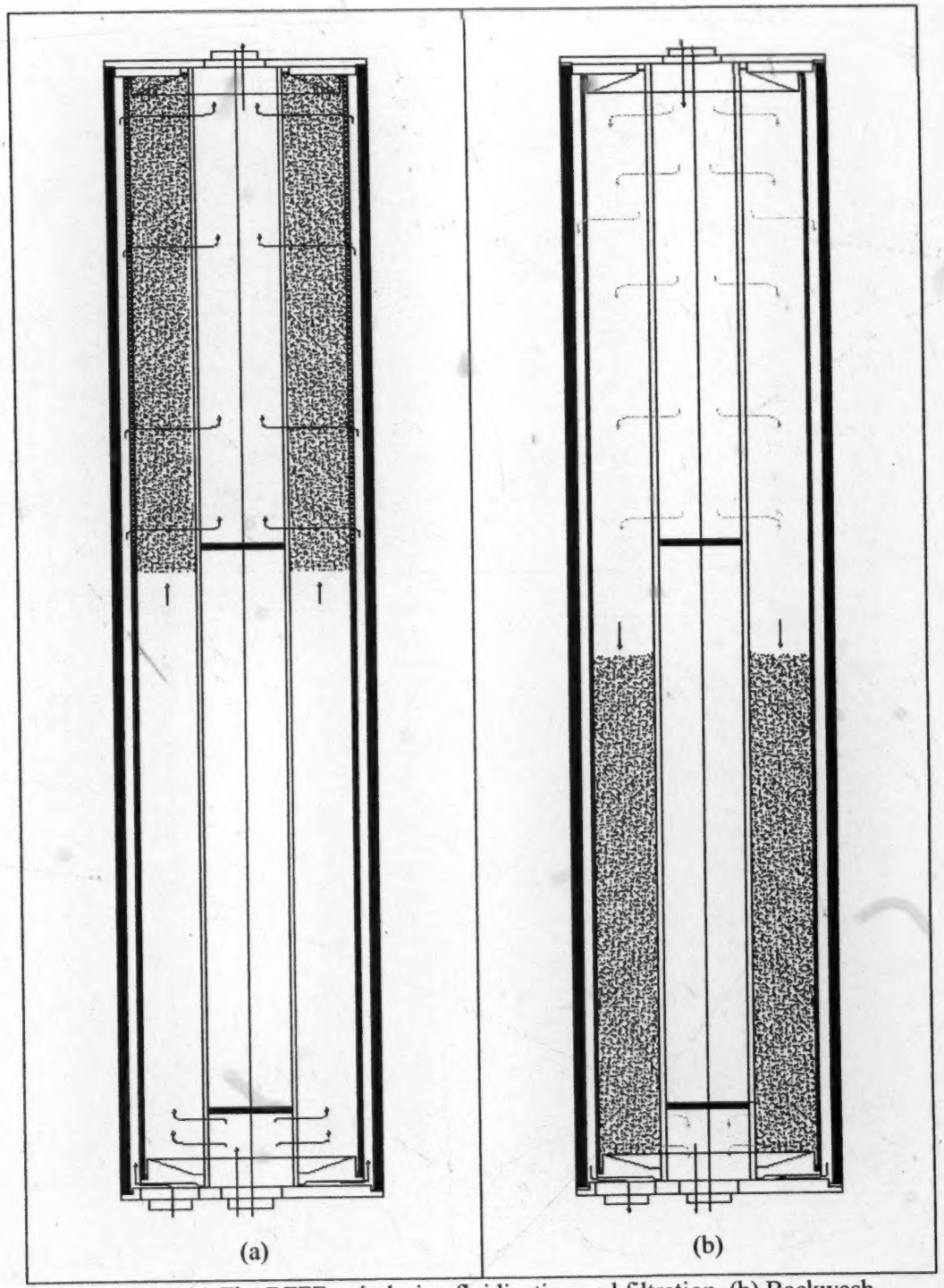


Figure 9. (a) The RFFF unit during fluidization and filtration. (b) Backwash.

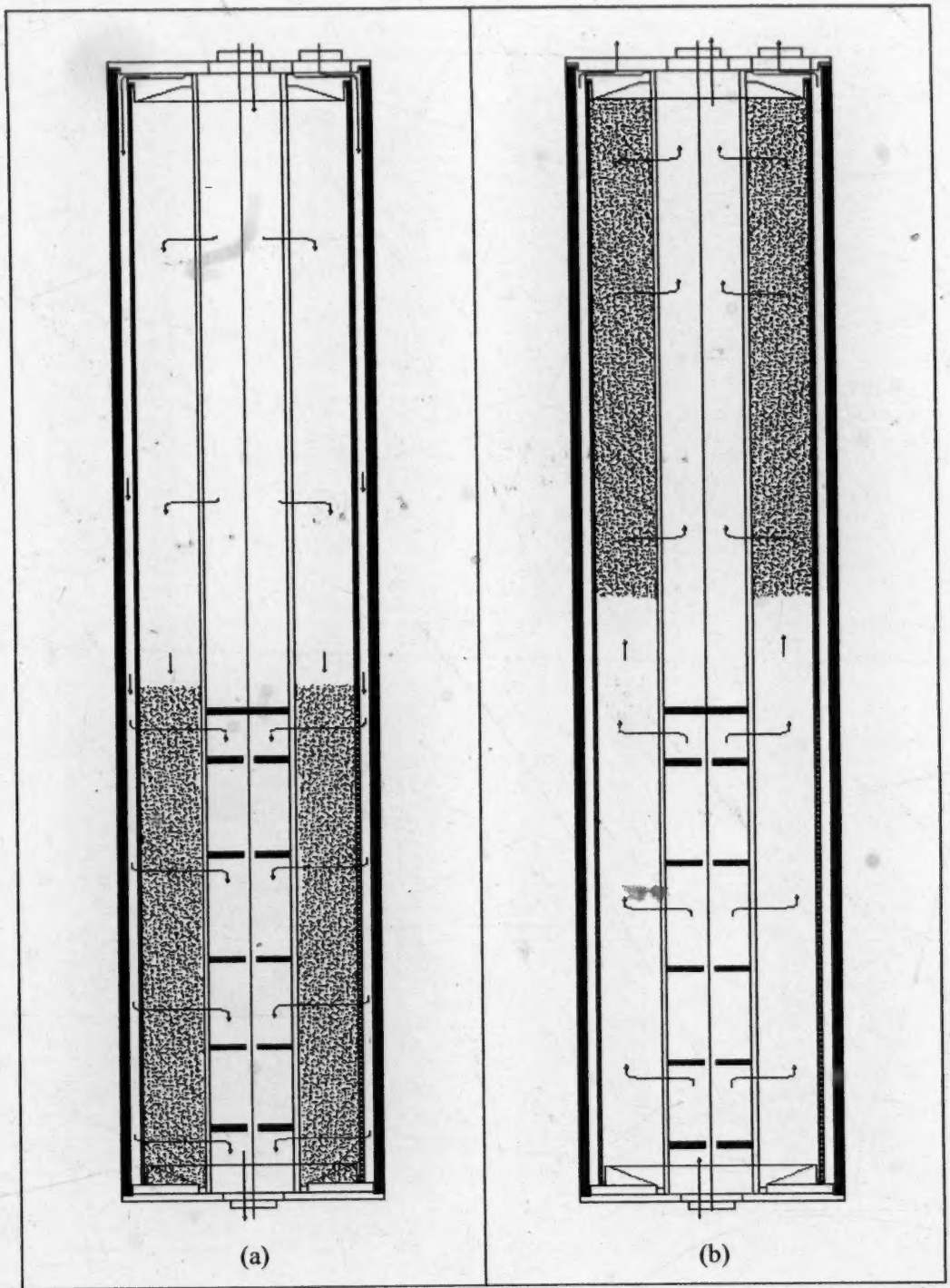


Figure 10. (a) The RFRF unit during filtration. (b) Fluidization during backwash.

4. EXPERIMENTAL SET UP

4.1. Experimental Apparatus

The experimental apparatus for the project consisted of four major components: the radial flow filter unit and related piping, particle and chemical delivery systems, instrumentation and data acquisition systems, and the air scouring system, which was added to improve backwash performance. A schematic diagram of the experimental apparatus was presented in Figure 11. Please note that the apparatus layout had been modified several times to fit both the RFFF and the RFRF units, and backwash operational changes.

Tap water was the only water source in the laboratory and was used as fluidization, filtration, and backwash water. Dirty water was simulated by adding ISO A2 fine dust in the mixing tank (see item 2 of Figure 11).

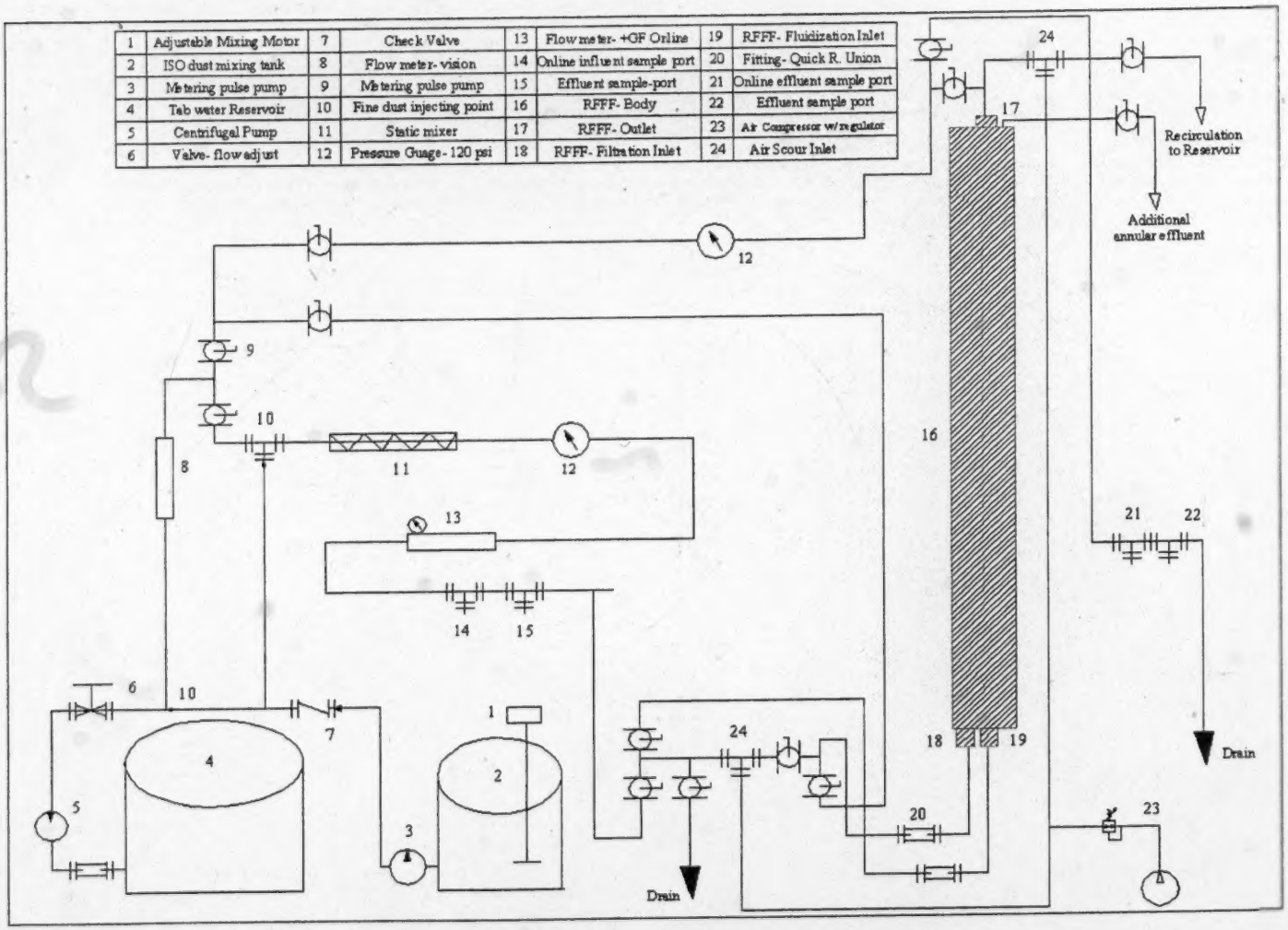


Figure 11. Schematic diagram of experimental apparatus.

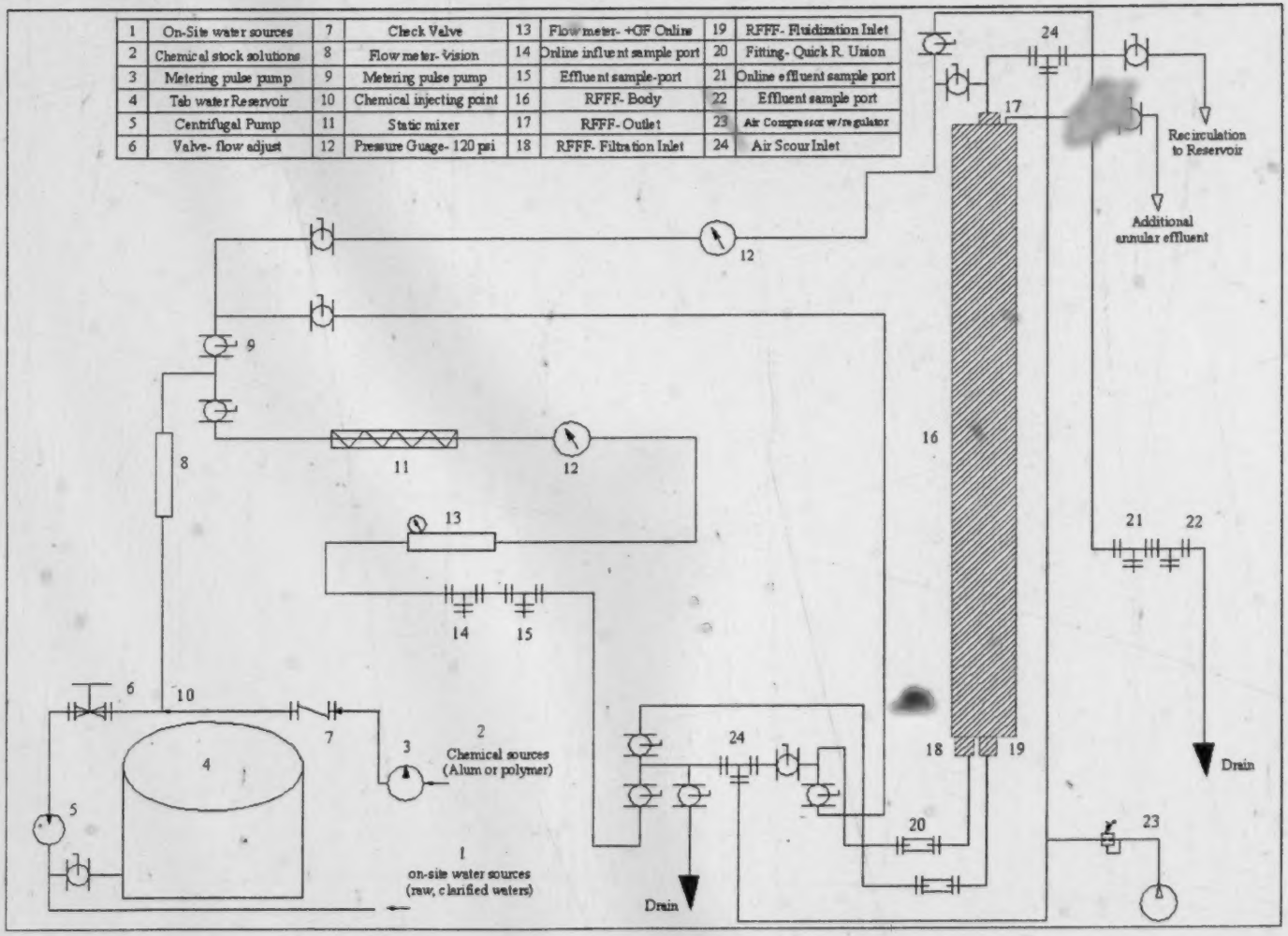


Figure 12. Schematic diagram of on-site experimental apparatus.

4.2. On-site Experimental Apparatus

The on-site experimental set up was similar to that in the laboratory, but the water sources were drawn directly from the pilot plant of the E.L. Smith WTP. Three kinds of water sources were available: the North Saskatchewan River Water (Raw), the plant's clarified water (C1 and C2 combined), and plant's filter influent water (C3). Clarifier 1 and Clarifier 2 were operated in parallel with three chemicals added to destabilize, settle particles and reduce organic compounds in the raw water. The chemicals added were alum, powder activated carbon (AC), and clarified polymer. Clarified water (C1 and C2 combined) flows to a re-carbon chamber (C3), in which only was minimum dosage of alum added (i.e. 1 mg/L) when the turbidity or particle counts were above a predetermined value. A schematic diagram of the experimental apparatus was presented in Figure 12. The illustrations of pilot plant set up can be seen in Figure 13 and Figure 14.

For sequence filtration purpose, filter system set up was modified to be able to retrieve filtrate from radial flow filter, which was stored in two 800 L reservoirs. Filtrate was then pumped to the next sequence radial filter, which had smaller filter media than the previous one.

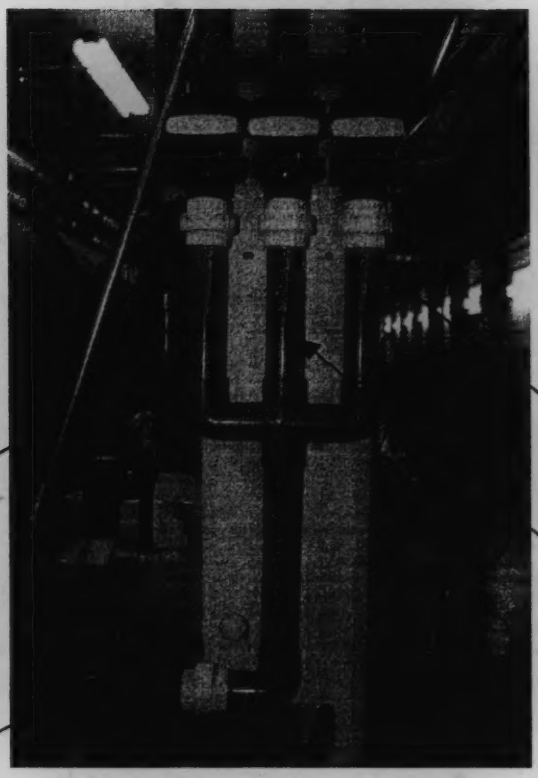

Raw water line (241 kPa)
Field Pump (max flow- 53 L/M)
Filter Influent (138 kPa clarified water from C1&C2 combined)
Filter Influent (138 kPa clarified water from C3)

Figure 13. Plant's water source lines.

Digital metering pump for accurate chemicals dosing (i.e. polymer.)
Raw water intake tunnel (250 ML/D)
Two 800 L water tanks can be used to store filtrate from RFF unit if in sequence filtration.
RFF units with modified piping for both RFFF and RFRF units. Drainage was designed based on the requirements of the E.L Smith WTP.
2" to 1" split point to provide raw and clarified water sources. Plant's filtrate influent (C3) was used as fluidized and cleaned water for RFF units.
Mixing tank was used to enhance mixing intensity for liquid polymer
Pressure air pump for RFF units. Remote video surveillance and data acquisition PC systems.

Figure 14. The RFFF unit layout in the pilot plant of the E.L. Smith WTP.

4.3. Particle, Spore, and Polymer Delivery System

There were two metering pumps used in these experiments, LMI Series A1 manual flow control and LMI A971 digital signal flow control metering pumps. Both pumps were fitted with a LE-155 liquid handling assembly. The digital signal control metering pump was wired with Signet flow transmitter to achieve desired consistent dosing to the filter influent line via an injection check valve. Those two pumps were installed according to manufacturer specifications. Immediately downstream of the injection point, the concentrated particle solution was mixed into the filter influent water via a 457 mm (18") Koflo inline static mixer. Observation of fluctuated particle loading to the filter system has led to change the particle injection point with a reducing bushing device in which the diameter of fitting was reduced from 38 mm (1.5") to 19 mm (0.75").

4.3.1. ISO A2 Fine Dust and Particle Delivery

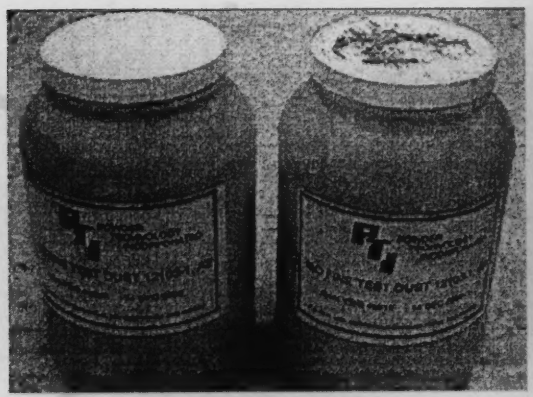
A stock particle solution was prepared by adding ISO 12103-1, A2 fine test dust from Powder Technology, Inc. to municipal tap water. The ISO A2 fine test dust was a relatively new replacement for AC fine test dust, from the AC-Delco division of General Motors; this product had historically been used in filtration studies but was no longer being manufactured. The manufacturer-supplied particle size distribution for the dust was reproduced in Table 5. Figure 15 shows the product of ISO A2 fine dust and particle delivery system. Figure 16(a) shows the size of A2 fine dusts in the SEM, ranging from 0.5 to >10 μm.

The stock solution was prepared to a concentration of 5 g/L in a 200 L tank. The solution was continuously mixed using a Barnant 9-900 rpm mixer was delivered to the system via a precision-flow metering pump, LMI A971. For simultaneously

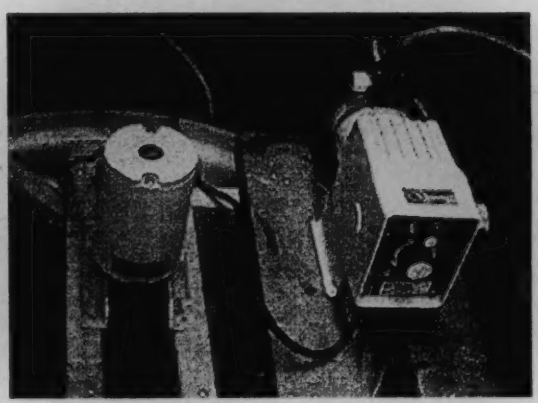
injections of *B. subtilis* spore and ISO A2 fine dust, the former one was introduced to the RFFF unit by digital LMI A971 metering pump while the latter one was injected by LMI A1 metering pump. Both pumps were fitted with the LE-155 liquid handling assemblies.

Table 5. Particle size distribution for ISO 12103-1 A2 fine test dust

Particle Size (μm)	Cumulative Percentage (% < Particle size)
1	2.6
2	10.7
3	19.5
4	27.8
5	35.1
7	44.8
10	53.4
20	71.8
40	89.3
80	99.9



(a) ISO 12103-1, A2 Fine Test Dust.



(b) 200 L tank, Barnant mixer, LMI A1 metering pump, and ¼" tubing.

Figure 15. ISO A2 fine dust and related particle delivery system devices.

4.3.2. Spore Delivery System

The above delivery system had been used for *Bacillus subtilis* spore injection with some modifications. *B. subtilis* spores were diluted to stock solution, 6.04 x 10^4 spores/mL, by adding 12.12 mL of mother stock (2.0 x 10^7 spores/mL) with 4 L ELGA water in a 4 L Erlenmeyer flask. Stock solution was continuously mixed in a 4 L Erlenmeyer flask by a Fisher stirrer. Mixing intensity was not measured but it was mixed well without vortexing. The spore solution was then injected to the RFFF unit according to the desired spore concentration via reducing bushing point by LMI A971 metering pump; meanwhile, ISO A2 fine dust was introduced to the system via the same injection point to compare log dust, log turbidity, and log spore removals. Figure 16(b) shows the size of *B. subtilis* spore and vegetative bacteria.

4.3.3. Polymer Delivery System

Only LT-7996 polymer was used as the coagulant in the on-site experimental work at the E.L. Smith WTP for direct filtration purpose. Descriptions of this particular type of polymer can be seen in Table 6. LT-7996 was found to be the optimal filter polymer in the E.L. Smith WTP in an internal study by Madsen (2001).

LT-7996 was diluted to 10% stock solution with D.I. water and stored in a 15 L covered bucket. Digital control LMI A971 pumps stock solution of polymer the radial flow filter system via reducing bushing injection point.

Polymer dosage was based the water quality with the polymer pump shutoff test described in the literature section (Cleasby et al., 1984).

Table 6. Polymer descriptions.

Name	PERCOL LT-7996
Supplier	Allied Colloids
Concentration (g/L)	1,000
Type of Material	liquid
Molecular weight	low
Charge type	cationic
Charge density	high
Application	coagulant/ coagulant aid

Information was provided by the E.L. Smith WTP.

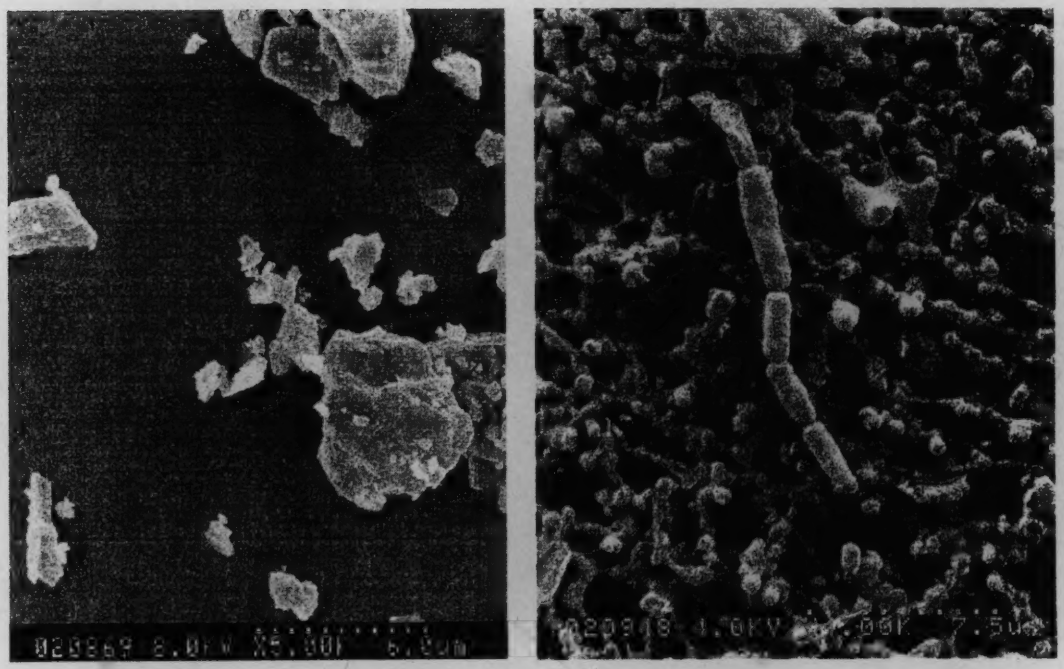


Figure 16. (a) ISO 12103-1, A2 fine dust in SEM (b) *Bacillus subtilis* spore and vegetative bacteria (HITACHI S-2500).

4.4. Spore Preparation, Generation, and Enumeration

Preparation, generation, and enumeration of *Bacillus subtilis* spores during the phase of filter challenge test runs can be found in the Appendix C. Procedures were modified from Leinan (2003).

All samples were collected in duplicate at each time intervals during the runs of filter challenge phase. Duplicate data were then averaged to compare with turbidity and particle count in each time interval. The data can be seen in the result section.

4.5. Instrumentation

Flow was monitored on the system filter influent line (mainstream) by an on-line Rotor-X paddle-wheel flow sensor with Signet digital transmitter. Pressure was monitored on both the filter influent line and backwashing line using two (0 to 1,100 kPa) oil-filled pressure gauges from WIKA, and for online monitoring and semi-auto pilot plant purposes a pressure transmitter was purchased. The pump was installed according to manufacturer specifications and was digitally calibrated to the influent line WIKA pressure gauge. Turbidity of the filter's influent and effluent lines was measured online using Hach Model 1720C low range turbidity meter and Hach Model 1720D low range turbidity meter, respectively. Both particle counts of the filter's influent and effluent lines were recorded using Hach 2200 PCX particle counters with Model PCX particle counting sensors. The data from the flow meter and influent turbidity meter was logged on the 4 to 20 mA analog signal wiring ports of the influent particle count meter, and the data from the influent particle count meter, effluent turbidity meter, and online pressure meter was logged on the 4 to 20 mA analog signal wiring ports of the effluent particle count meter. A Pentium III computer running Hach 2200 PCX OPC Software was logged on the effluent particle count meter via the 4 to 20 mA analog signal wire. The effluent particle count meter communicated with the

computer via a RS-232 to RS-485 converter that interfaces with the computer's serial port. The particle count meters processed the 4 to 20 mA signals from the flow meter, turbidity meters, and pressure meter and transferred the signals to the Hach software where they were converted to digital flow, pressure, and turbidity data. Figure 17 shows the layout of instrument set up and Figure 18 shows the above-described instruments.

During intensive filter experiment runs, it was found that backwash by water fluidization alone was insufficient to clean glass beads in the filter. Baylis (1959) and Amirtharajah (1978) also indicated that the weakness of backwashing by water was attributed to a lack of any abrasion between the grains in a fluidized bed. For that reason, backwash was assisted by an auxiliary scouring system with an installation of air pump. As all the glass beads were contained in the outer cylinder space by fine screens, there was no substantial danger of losing some of the medium if air souring was used during overflow; however, caution should be taken to avoid failure of the fine screens.

A Campbell 3.73 kW (5 HP) air compressor was mounted on a 118 L (26 Gallon) cylindrical tank to provide sufficient airflow via 12.8 mm (½") flexible high-pressure hoses. Two injection points were in the bottom and top of filter assemblies. The related piping assembles can be seen in the following Figure 19.

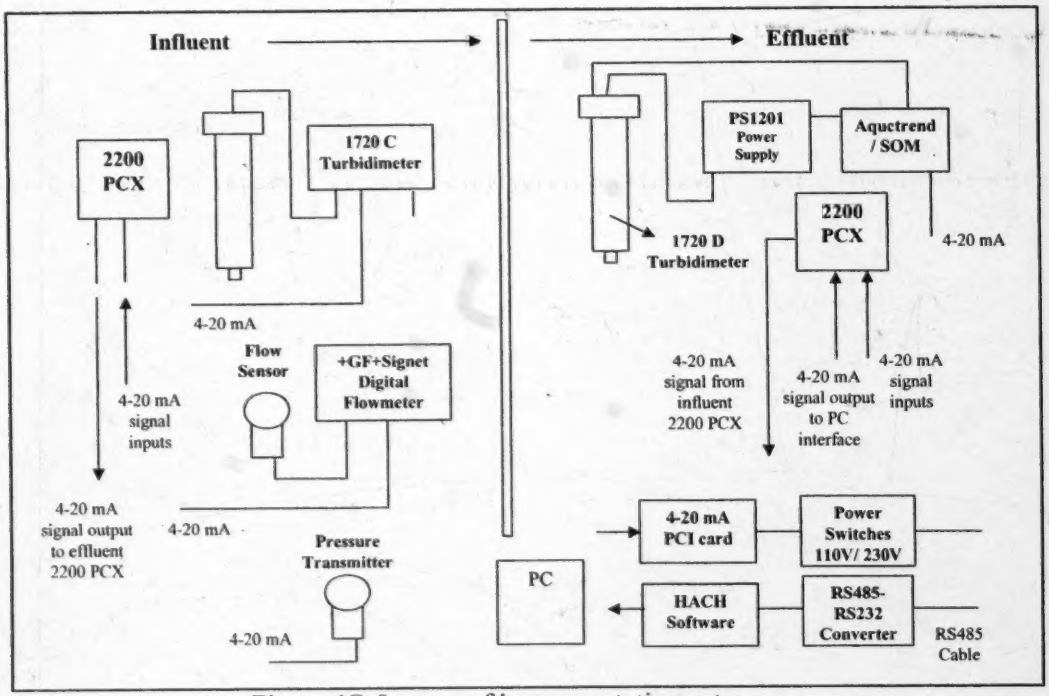
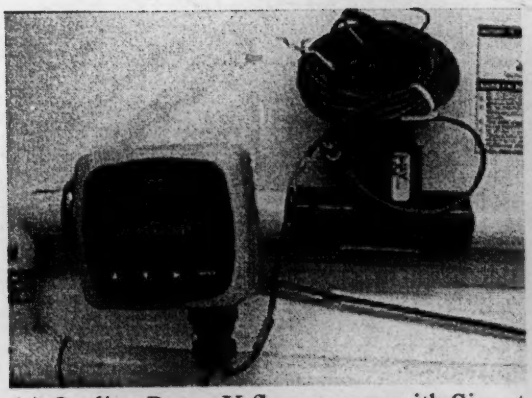
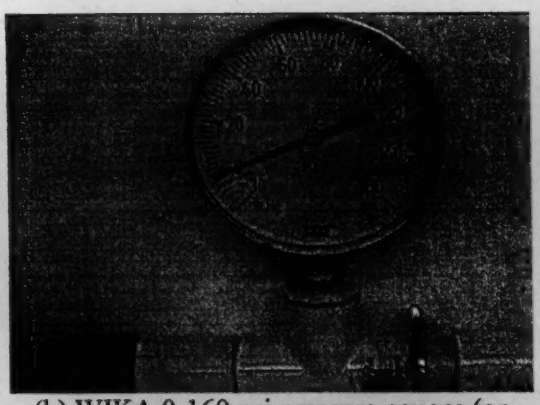


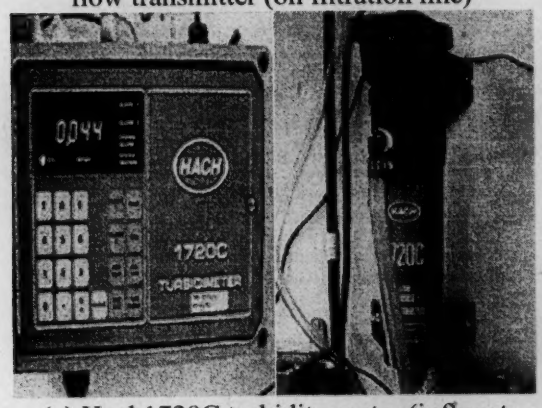
Figure 17. Layout of instrumentation set up.



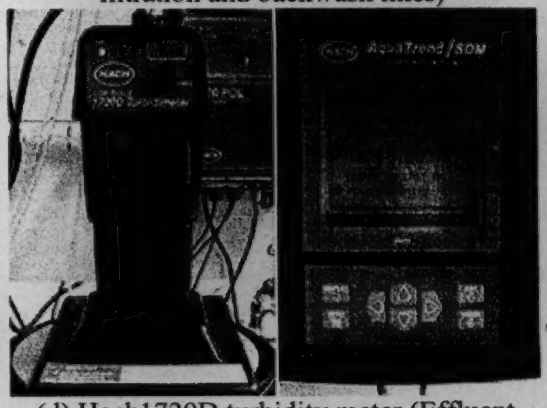
(a) On-line Rotor-X flow sensor with Signet flow transmitter (on filtration line)



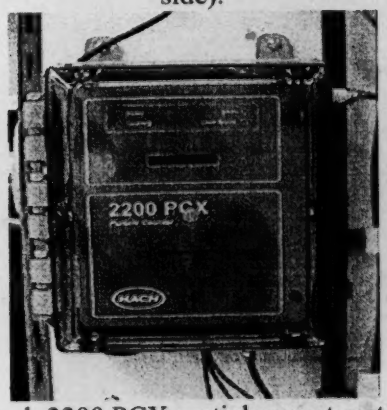
(b) WIKA 0-160 psi pressure gauges (on filtration and backwash lines)



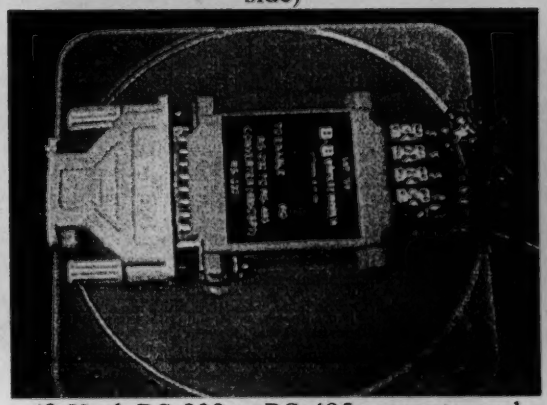
(c) Hach1720C turbidity meter (influent side).



(d) Hach1720D turbidity meter (Effluent side)

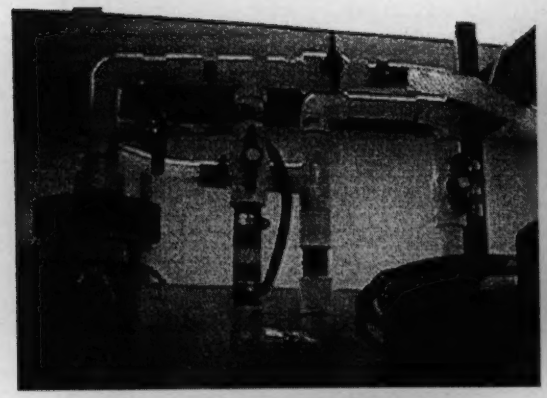


(e) Hach 2200 PCX particle count meter (on both influent and effluent sides)

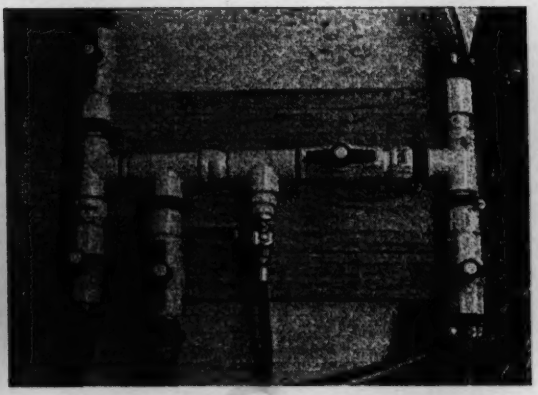


(f) Hach RS-232 to RS-485 converter and PCX OPX software.

Figure 18. Instrumentation.



(a) Top air scouring inlet point.



b) Bottom air scouring inlet point.

(c) Auxiliary air scouring system.

Figure 19. Auxiliary air scour system and air injection points in the top and bottom of filter related piping assembles.

Note that high pressure air was introduced to the filter during backwashing to provide an additional abrasion to the filter media to improve the effectiveness of cleaning media and fine screens.

4.6. Data Collection and Analysis

Data collected on the computer was recorded at half of minute to one minute intervals throughout filter operations. Particle count measurements were made over a number of different size ranges. For the purposes of the present project, data was collected for the following particle six size ranges: 2 to 4 μm, 4 to 8 μm, 8 to 12 μm, 12 to 15 μm, >2 μm, and >15 μm.

The flow meter, pressure gauge, and both the turbidity meters and the particle counters were calibrated according to manufacturer specifications at the start of the project and calibration was periodically verified throughout the filter runs. Pressure measurements were determined manually throughout the preliminary filter runs and were recorded in the project logbook. Since August 2002, a digital pressure gauge was installed and calibrated to transmit online pressure data to the acquisition system. Figure 20 provides a close up view of the automatic data acquisition system.

The recorded file was then opened in the preset MS-Excel spreadsheet to have preferred charts (i.e. percent particle removal over time, turbidity over time, flow and pressure over time, etc) and calculated statistical data (i.e. run time, filter capacity, log removal, etc.). Comparisons of runs were made possible by those explicit Excel format.

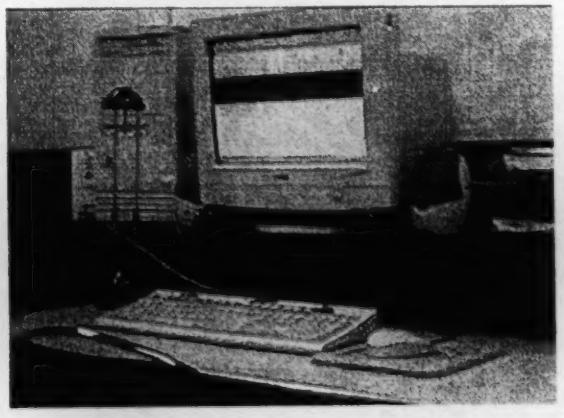


Figure 20. Data acquisition system.

5. PRELIMINARY RESULTS

This section provides all the data of laboratory-based testing runs from the on-going revised RFFF unit. Even though those data did not provide statistical consistency, it was important for both filter manufacturer to redesign a more reliable filter unit and the experimental set up design to optimize the experimental parameters. The data for the redesigned RFFF and the RFRF units were shown in the next result section. Note that ripening time was calculated from the start to the filter ripening point, which was either the 85% >2 μm particle removal point on Mil-Spec 10 runs or the 90% >2 μm particle removal point on Mil-Spec 12 and 13 runs. System run time was counted from the ripening point to the end of the run, which was set to 350 kPa (50 psi), 415 kPa (60 psi), and 480 kPa (70 psi) on Mil-Spec 10, 12, and 13, respectively. This run time duration was used to calculate treated water volume and percentage particle removal. Influent and effluent particle and turbidity readings were represented by median values from the start to the end of the system run.

Every first run (e.g. P10-1) of the filter media used clean screens and glass beads from sealed bags received from John Martin Company. As the filter was exhausted by filtration, filter media, screens, and filter assembles were cleaned by backwash which protocols were stated in the Appendix A. Then the following run (e.g. P10-2) with the same filter media and either the same or different experimental parameters was conducted accordingly.

5.1. Issues Related to Filter Parts

Data of ten experiment runs based on ongoing modified RFFF filter unit, six runs with Mil-Spec 10 glass beads and four runs with Mil-Spec 12 glass beads were shown in Table 7. Thin polyester screens, 43 μm sieve opening, were used in this testing step to contain glass media in the filter unit. The highest filter performance run, 10-1, was

greater than 97% in terms of > 2μm particle removal on Mil-Spec 10 filter media while the lowest one, 10-6, on the same media achieved only about 70%. The same significantly fluctuated performance over the highest, 12-4, and the lowest, 12-1, runs on Mil-Spec 12 filter media was 95% and 60%, respectively.

There were testing runs other than the ten runs presented in the table, but due to poor results and improper parameter settings they would not be presented. Some major failures of filter unit, related piping, and instrumental systems had been observed and solved. Others minor failures had been left until new parts for the filter unit arrived. Therefore, a substantial time delay occurred in the research timeframe.

The system cut-off point was selected according to either the fluidization failed due to low flow velocity or breakthrough occurred. In the latter case, breakthrough was observed by effluent particle count reading and percent particle removal curves. In some situations, the system was stopped based on unforeseen RFFF unit failures. System run time was counted from the ripening point, 85% over >2 μm particle removal, to the available pressure drop point, 350 kPa (50 psi) over the initial pressure head. Percentage particle removal was calculated from the initial point to the end of the system run, and it might be higher if being calculated from the ripening point to the end of system run. However, some runs couldn't reach the ripening point even at the end of the system run.

Fluctuating particle loadings to the filter unit led to an installation of a digital control metering pump to replace the previous manual control pump. Note that particle loading was controlled by manual adjustment based on observation of filter influent particle count, and digital control metering pump receives analogue signals from online flow meter to provide desired flow based on real-time mainstream flow. Influent and effluent particle counts/mL readings showed significant improvement for run P10-3 (see Figure 21) and run P10-4 (see Figure 22).

Table 7. Summary of preliminary operational conditions in the RFFF filter runs. Note that the screens used in those tests were thin polyester.

Run	Media (Mil-Spec)[a]	Initial flow rate m/h	Run time (min)	Influent particle counts (>2 μm)/mL Median	Effluent particle counts (>2 μm)/mL Median	Percentage particle removal (>2 μm) Median	Notes
P10-1	10	10.7	-*	5048	18	97.66	P[1]
P10-2	10	10.7	158	12763	410	95.21	P
P10-3	10	11.0	186	13897	409	96.40	P
P10-4	10	11.0	-*	17757	3457	79.94	F[2]
P10-5	10	10.6	-*	16136	1404	91.07	P
P10-6	10	10.6	-*	16899	4918	70.07	F
P12-1	12	10.6	-*	13322	5299	60.30	F
P12-2	12	10.7	-*	16370	7897	51.58	F
P12-3	12	10.3	362	17174	1966	88.43	F
P12-4	12	10.7	-*	17719	883	95.01	P

-* data was not available as either 350 kPa pressure drop or ripening point or both were not reached.

[a] Military-Grade glass beads. Specification of size corresponding to numbers of Mil-Spec can been seen in Table 4.

P[1] indicate no major failures were observed while F[2] presents some degrees of system failures.

Some observations of system failures can be seen in the Figure 23, which were attributed to the significant deteriorations of system performance on filter unit. Besides, inconsistent particle loading introduced by the defective metering pump and injection fittings might also attribute to the poor system performance. This problem was later solved by replacing the valves, fittings, etc. to overcome backflow from the mainstream. The pressure was increased gradually as pressure drop occurred on declining rate operational filtration. Plus, a new injection point applied reducing bushing also solves the back flow problem (see section 2.6).

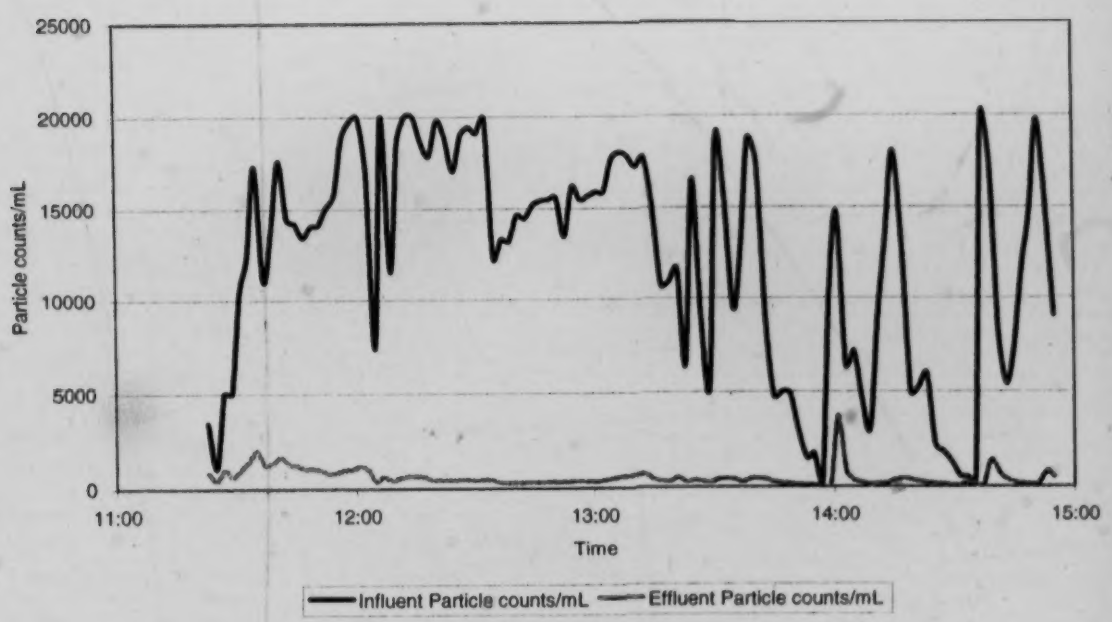


Figure 21. Particle loading over time on run, P10-3.

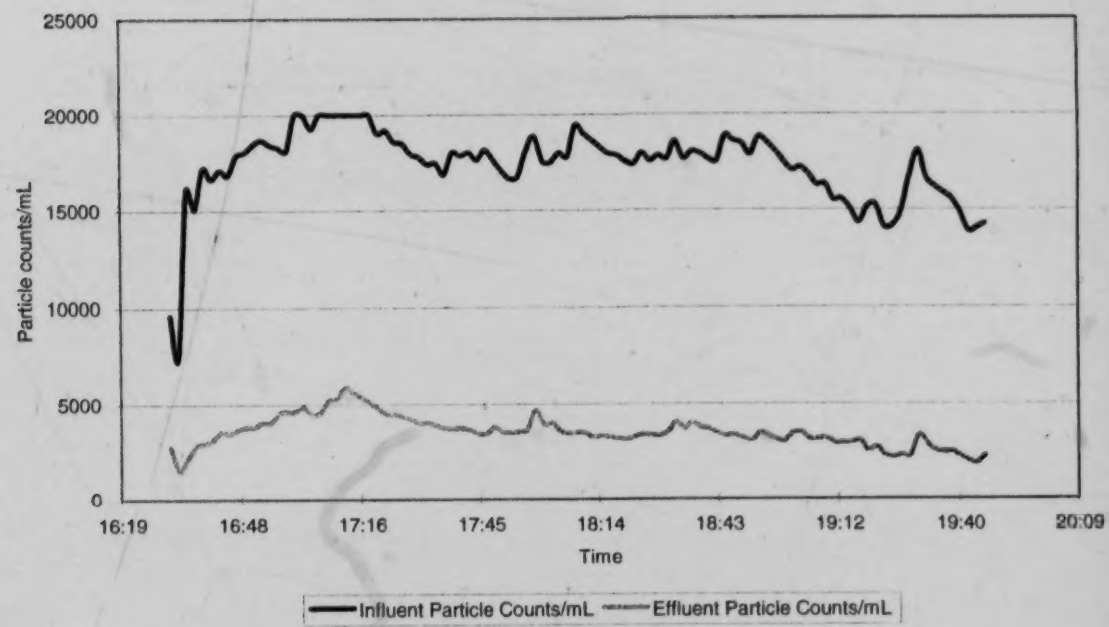
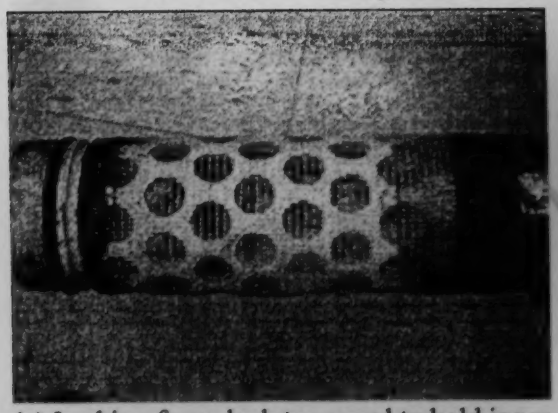


Figure 22. Particle loading over time on run, P10-4.



(a) Leaking from duck tape used to hold inner screen.

(b) Leaking from Top and Bottom Caps.

(c) Failure of O-ring seal. Glass beads escaped from cylinder space to annular space and were lost to drain.

(d) Failure of fluidization due to suction flow at the bottom of inside cylinder. Inner screen and duck tape were the two major effects.

Figure 23. Major system failures during preliminary system runs.

5.2. Issues Related to Screens

After the above testing runs, thin polyester screens were replaced by the polyvinylidene fluoride (PVDF) screens, which sieve opening size was reported at 43 μm by the screen manufacture and observed at 70 to 150 μm on SEM due to the lack of durability. Three testing runs with Mil-Spec 13 filter media on PVDF screens were conducted, and results showed that the screens were blocked by filter media itself because the size of Mill-Spec 13 filter media, 40 to 90 μm, were smaller than the sieve opening of screens. Besides, there was no ripening time issue for those runs and the level of glass bead height was decreased run after run; as a result, loss of glass beads and blocked screen issues were very obvious. Data of those three runs can be found in Table 8.

Following those Mil-Spec 13 runs, four tests, 10-1 to 10-4, based on Mil-Spec 10 filter media were performed because the sieve opening of PVDF screen was small enough to contain Mil-Spec 10 glass beads. However, since PVDF screens were blocked by previous runs with Mil-Spec 13 glass beads and were not able to be cleaned by standard backwash, results from those four runs were poor in terms of filter capacity, which were caused by high pressure drop. Data from runs, V10-1 to V10-4, conducted on Mil-Spec 10 filter media with brand new PVDF screens can be seen in Table 9.

Overall performance in terms of >2 μm particle removal of runs, 10-1 to 10-4, and V10-1 to V10-5, was 95.2% ± 1.02% and 89% ± 3.5%, respectively. The relatively high particle removal efficiency of runs, 10-1 to 10-4, was the result of screen blockage. Runs, V10-1 to V10-5, have similar or less particle removal efficiency compared to runs with thin polyester screens in the preliminary result. The slightly decreased efficiency was attributed to the larger sieve opening of PVDF screens than that of thin polyester screens (see (a) and (b) of Figure 28).

Table 8. Summary of runs based on Mil-Spec 13 filter media in the RFFF unit. Runs of 13-1 through 13-3 were tested using PVDF while those of T13-1 through T13-6 were conducted using Teflon screens.

Run	Media (Mil-Spec)[a]	Initial flow rate (m/h)	Initial pressure (kPa)	Ripening time (min)	Run time (min)	Treated volume (m^3)	Influent turbidity (NTU) Median	Effluent turbidity (NTU) Median	Influent particle counts (> 2μm)/mL Median	Effluent particle counts (>2 μm)/mL Median	Percentage particle removal (>2 μm) Median
13-1	13	15.0	145	0	106	3.91	1.6	0.08	16438	269	98.4
13-2	13	14.0	118	0	103	3.55	1.6	0.08	15691	214	98.6
13-3	13	16.0	207	0	94	3.61	1.6	0.08	15741	464	97
T13-1	13	15.0	128	39	134	5.95	1.0	0.14	10996	409	96.9
T13-2	13	15.0	135	14	64	2.64	1.2	0.23	11810	736	94.2
T13-3	13	18.0	197	0	70	2.81	1.2	0.16	12169	414	96.7
T13-4	13	19.0	200	15	135	2.72	1.6	0.16	14415	822	94.9
T13-5	13	19.0	186	35	170	3.61	0.78	0.16	6638	535	94.6
T13-6	13	19.0	208	14	196	4.22	0.4	0.1	3074	108	99.1

[a] Military-Grade glass beads. Specification of size corresponding to numbers of Mil-Spec can be seen in Table 4.

Table 9. Summary of operational conditions on Mil-Spec 10 filter media in the RFFF unit. Runs of 10-1 through 10-5 were tested using blocked PVDF while runs of V10-1 through V10-4 were conducted using new PVDF screens.

Run	Media (Mil-Spec)[a]	Initial flow rate (m/hr)	Initial Pressure (kPa)	Ripening Time (min)	Run Time (min)	Treated volume (m^3)	Influent turbidity (NTU) Median	Effluent turbidity (NTU) Median	Influent particle counts (>2 μm)/mL Median	Effluent particle counts (>2 μm)/mL Median	Percentage particle removal (>2 μm) Median
10-1	10	17.2	131	16	22	0.92	1.6	0.13	15890	795	95
10-2	10	14.5	124	0	23	0.73	1.6	0.15	16900	1009	94
10-3	10	12.7	97	0	66	2.21	1.2	0.1	12502	565	96.5
10-4	10	12.1	76	0	62	2.33	1.2	0.13	12698	586	95.4
V10-1	10	17.5	114	11	89	4.59	1.5	0.23	15129	1161	92.5
V10-2	10	17.0	117	33	94	5.16	1.5	0.25	15263	2033	87.2
V10-3	10	18.0	138	44	76	3.93	1.6	0.3	15486	2510	84.6
V10-4	10	12.5	73	33	114	4.56	1.6	0.28	14936	1566	92.7
V10-5	10	12.5	73	44	348	12.95	0.78	0.18	8334	1038	88.1

[a] Military-Grade glass beads. Specification of size corresponding to numbers of Mil-Spec can been seen in Table 4.

Figure 24 and Figure 25 show the pressure drop over time on runs, 10-1 to 10-4, and runs V10-1 to V10-5, respectively. Pressure increases were slower on runs V10-1 to V10-5 versus runs 10-1 to 10-4, which resulted in longer filtration run time.

Figure 26 and Figure 27 present the percentage particle removal (>2 μm) over time. The decreased particle removal on runs, V10-1 to V10-5, can be explained by the removal of thin precoat layer, which was formed by particles and glass beads in between screen and filter media surface. However, particle removal was still higher and less variation than the result, 88.3% ± 4.1%, reported by Baxter et al. (2001) on the same Mil-Spec 10 filter media. The blockage of the PVDF screens was proven by SEM picture shown in Figure 28 (c). Relatively high pressure drop over run time have led to another complete examination of the PVDF screens. A picture taken by SEM (Figure 28 (d)) showed that the sieve opening areas were not uniform, especially when the void ratio was almost zero in some areas.

Teflon screens, which sieve opening was reported and double checked at 37 μm by manufacture and SEM, were used to replace PVDF screens on another six runs based on Mil-Spec 13 filter media. Three runs of using PVDF screens and six runs of using Teflon screens were summarized in Table 8.

Overall performance in terms of >2 μm particle removal of runs, 13-1 to 13-3, and T13-1 to T13-5, was 98% ± 0.89% and 96.1 ± 1.9%, respectively. Zero ripening time and high initial pressure from run 13-1 to 13-3 were evidences that the PVDF screens were blocked by glass beads. Percentage particle removals of runs 13-1 to 13-3 were relatively higher than those of run T13-1 to T13-6, and this can be explained by similar precoat filtration, in which a finer coat of materials in front of a relatively larger filter media. Difficulties of backwashing the RFFF filters from runs of T13-2 to T13-4 brought a combined flow of air scouring and backwash water to enhance pulse pressure on screens and abrasion on filter media. As a result, data of runs T13-5 and TA13-6 shows improved backwash operation due to the drop of initial pressure, elevated ripening and system run times, and increased filter capacity. Note that a pressure

transmitter was installed after run T13-4 to provide online monitoring and data recording. A pressure regulator was attached to the drainage outlet to provide pressure ranged from 35 to 60 kPa depending on the effluent flow rate to have enough water flow to the effluent instruments.

Finally, thick polyester screens were manufactured to replace all the previous screens, which had higher void ratio to prevent screen blockage problem by either particles or filter media, and smaller enough sieve opening to contain filter media. Plus, significant cost reduction was another reason to switch screens from Teflon to thick polyester. Durability tests used air scouring and water flow for numerous cycles showed that the thick polyester screens were stronger than their predecessors. This particular type of screen was used in all experiments thereafter. Laboratory-based tests on the RFRF unit and on-site water treatment tests were conducted with this type of thick polyester screen. Detail data were presented in the next result section.

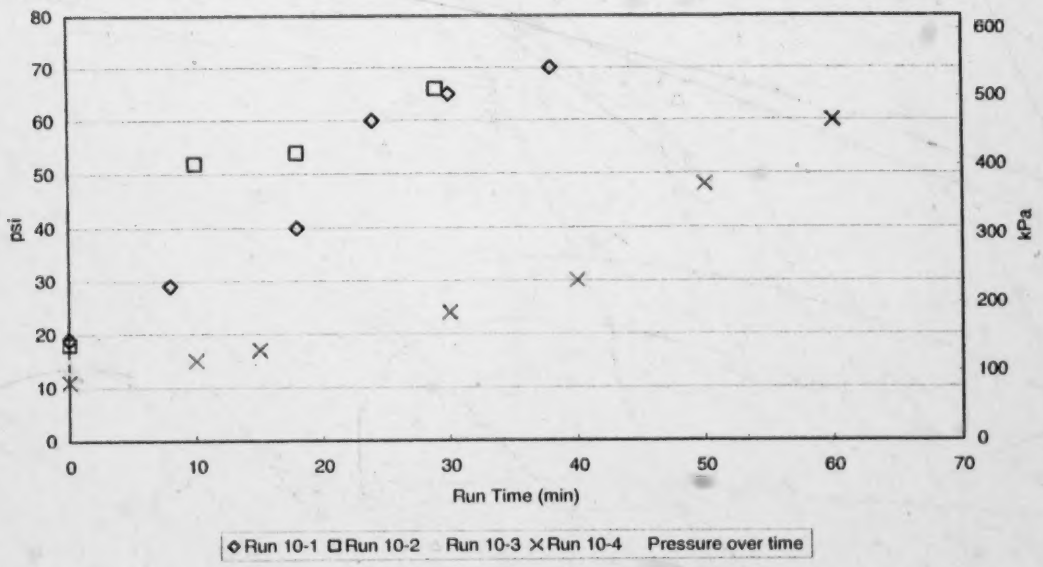


Figure 24. Pressure increase over time for Runs 10-1, 10-2, 10-3, and 10-4.

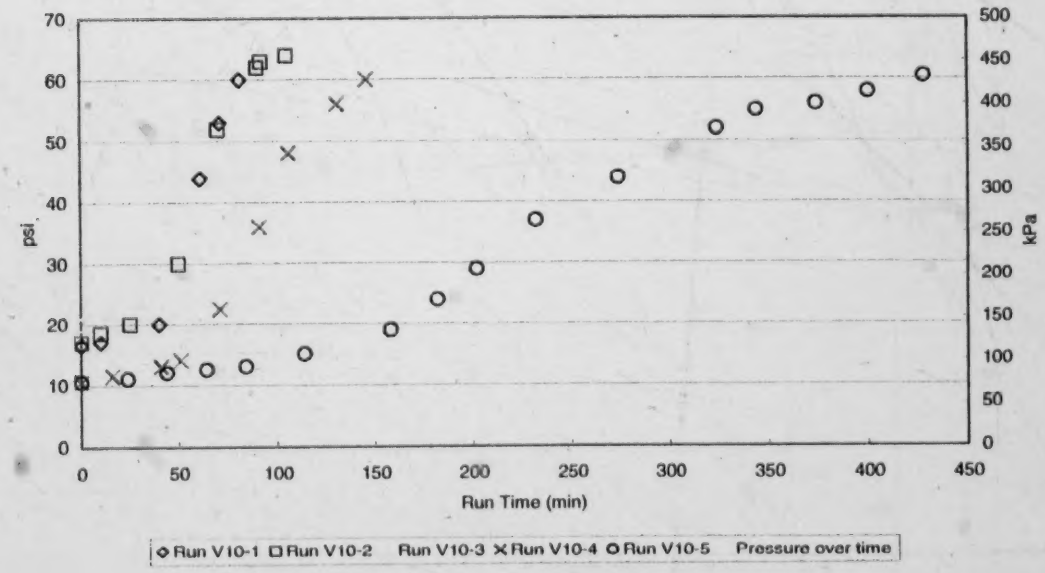


Figure 25. Pressure increase over time for Runs, V10-1 to V10-5.

Note that Runs of 10-1 through 10-4 were tested using blocked PVDF while runs of V10-1 through V10-5 were conducted using new PVDF screens with Mil-Spec 10 media.

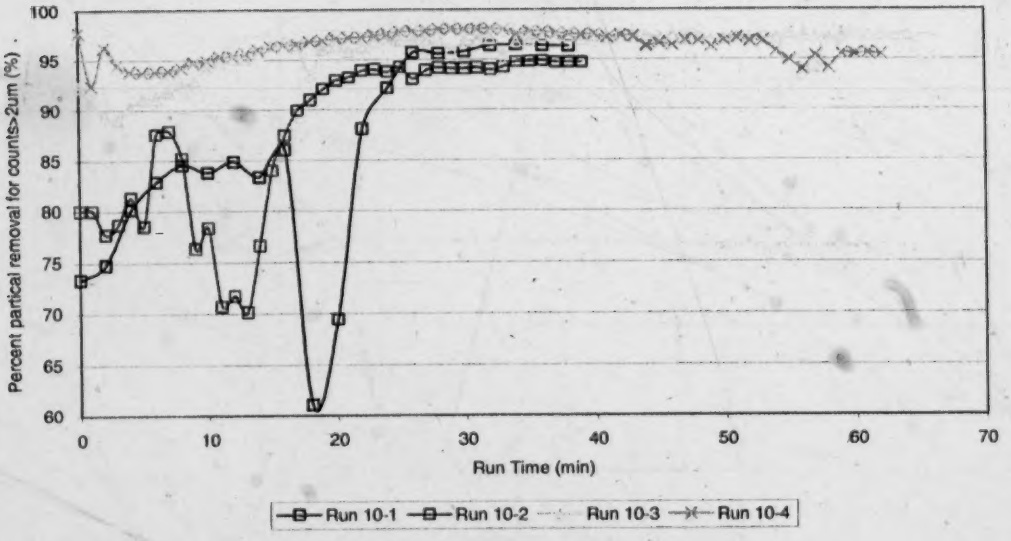


Figure 26. Percent particle removals over time for Runs 10-1, 10-2, 10-3, and 10-4.

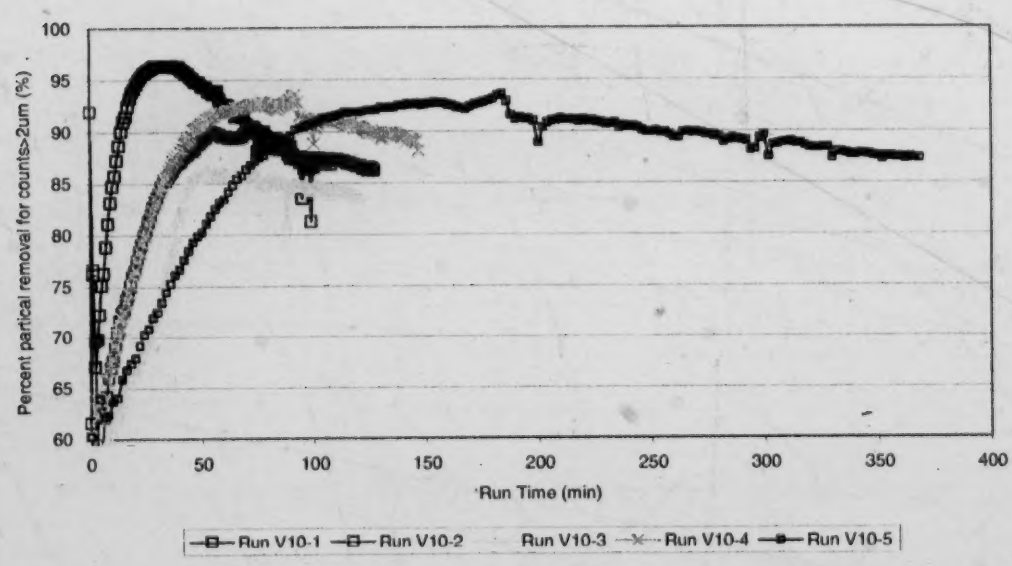
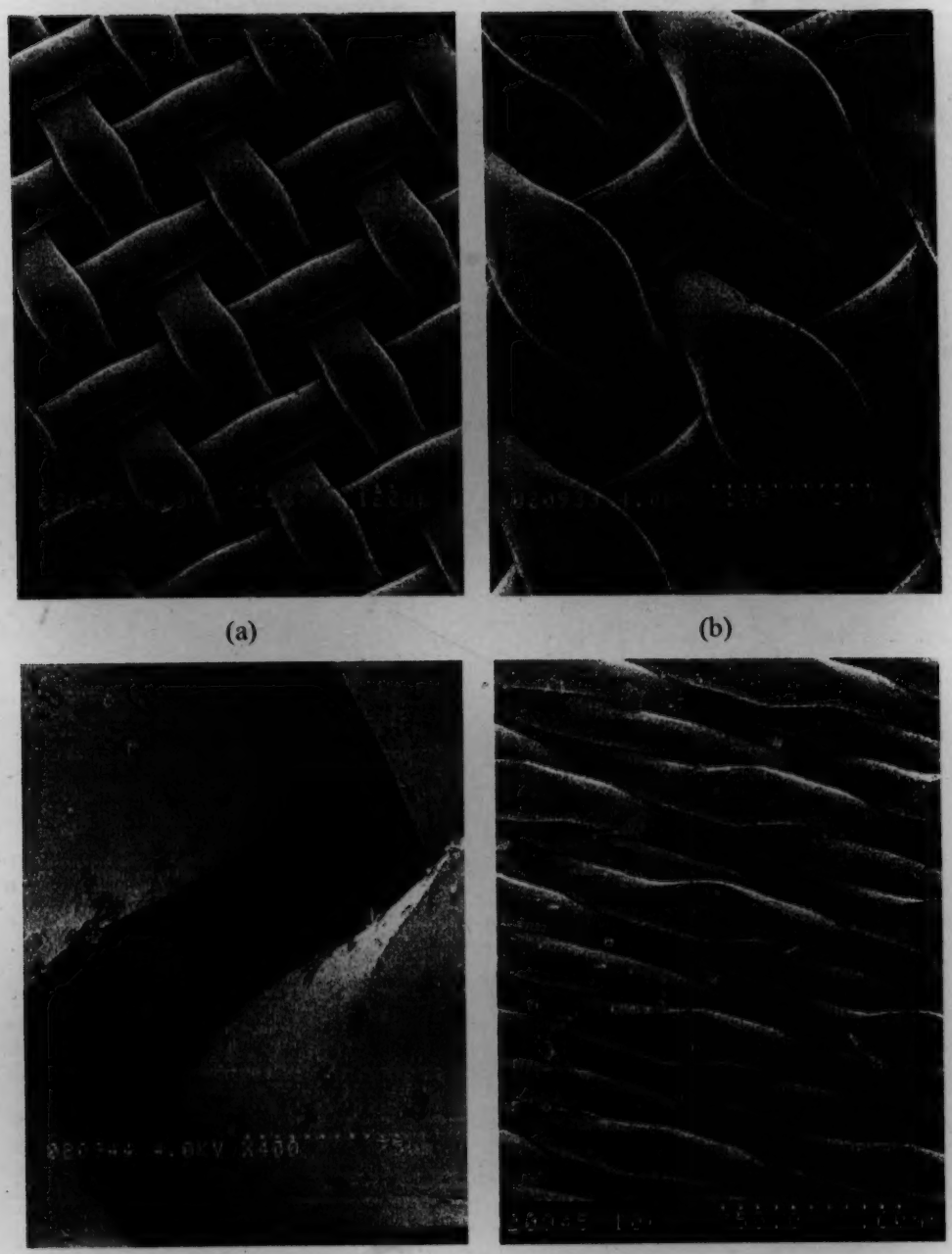


Figure 27. Percent particle removals over time for Runs, V10-1 to V10-5.



(a) (b)

(c) (d)

Figure 28. Examinations of screen issues using SEM (HITACHI S-2500).

(a) Thin polyester screen in SEM, 250X. (b) PVDF screen in SEM, 100X. (c) Mil-Spec 13 glass bead was trapped by PVDF screen's sieve opening, 400X (d) Void ration of PVDF screens was minimum, which result in high pressure drop due to screen blockage, 50X.

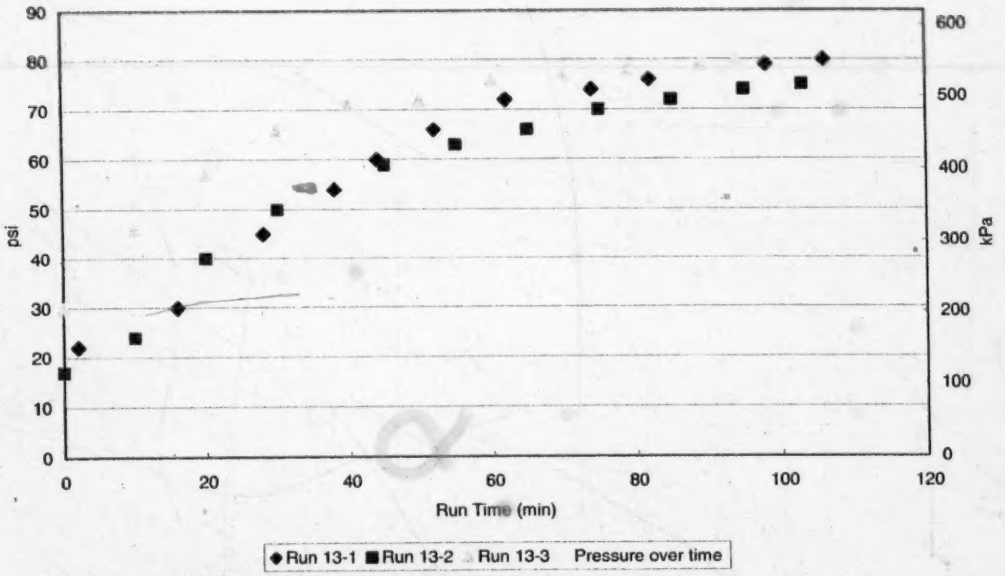


Figure 29. Pressure increase over time for Runs 13-1, 13-2, and 13-3.

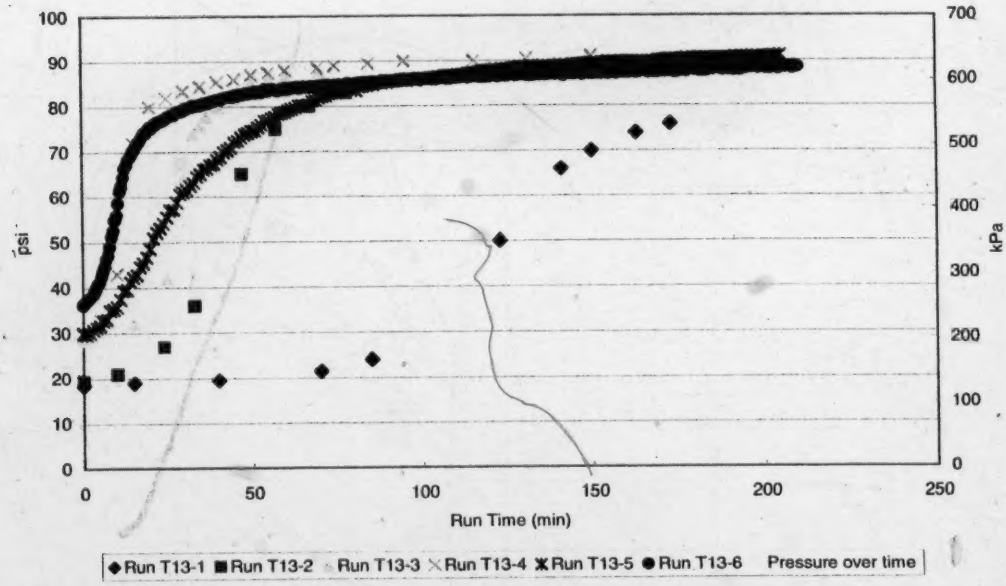


Figure 30. Pressure increase over time for Runs T13-1 to T13-6.

Note that Runs of 13-1 through 13-3 were tested using PVDF while those of T13 through T13-6 were conducted using Teflon screens with Mil-Spec 13 media.

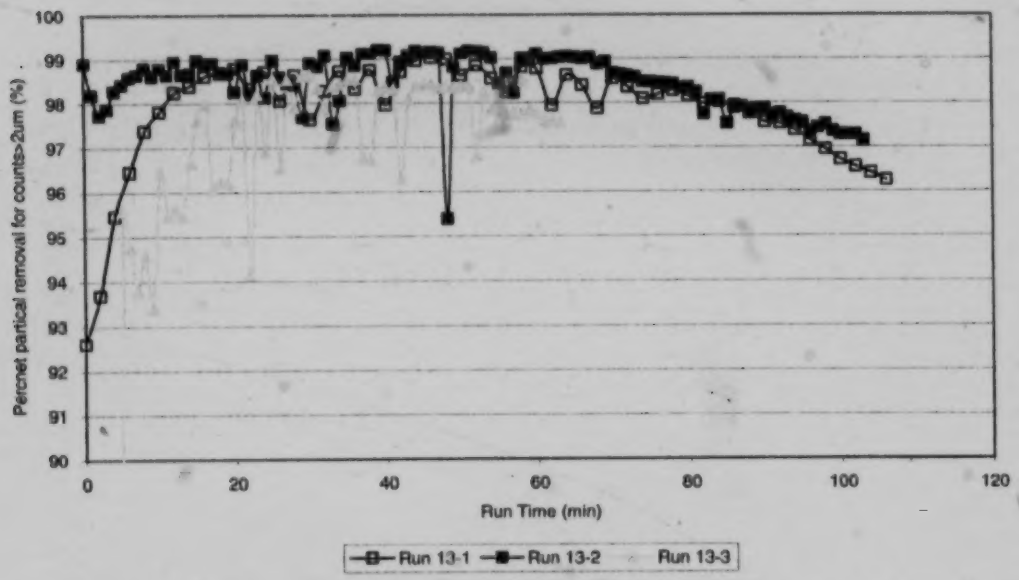


Figure 31. Pressure increase over time for Runs 13-1, 13-2, and 13-3.

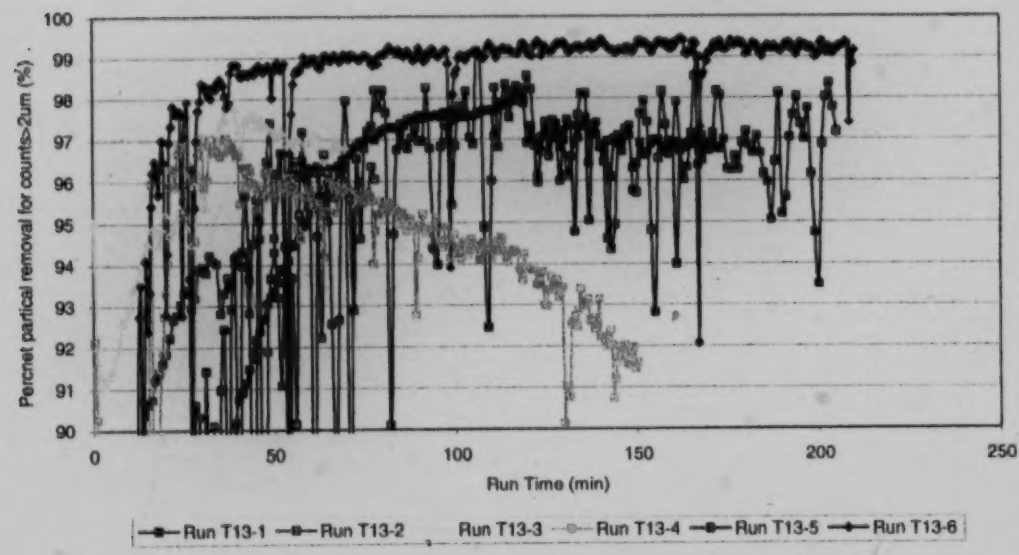


Figure 32. Pressure increase over time for Runs T13-1 to T13-6.

6. RESULTS

There were two major improvements on filter parts designed by John Martin Company in the early July 2002. First was the top and bottom head assembles, which allowed better sealing of the three pipes and provide extra outlets to have better flow controls in terms of fluidization, filtration, and backwash. Second was that the thick polyester fine screens replaced all previous screens which were the source of many system failures. Note that the function of screens was to contain filter media, glass beads, in the cylinder space. Filter performance was improved in terms of consistency and durability as compared to the data in the preliminary section, and no system failures were observed thereafter.

Four sections are presented in this chapter. First, the data generated from the laboratory-based experimental runs after the preliminary testing phase. Second, the results from filter challenge tests using *B. subtilis* spores. Third, the data generated from on-site pilot plant study. Finally, filter-aid polymer filtration tests in the on-site pilot plant were presented. Note that the ripening time was calculated from the start to the filter ripening point, which was the threshold of either the 85% particle removal (>2 μm) on Mil-Spec 10 runs or the 90% particle removal (>2 μm) on Mil-Spec 12 and 13 runs. System run time was counted from the ripening point to the end of the filtration run, which was set at 4.5 m/hr (4.5 GPM) instead of 350 kPa pressure drop in the preliminary runs because initial pressure was increased by the installation of an effluent pressure regulator, 35 to 60 kPa; plus, as the cut-off point was set to 4.5 m/h, longer filter run time was expected. The run time duration was used to generate treated water volume, percentage particle removal, and backwash percentage over treated water volume. Influent and Effluent particle and turbidity readings were presented as median values from the start to the end of the system run.

6.1. Laboratory-Based Tests

Due to limited time and resources, all runs based on certain filter media were conducted with different sets of screens. Although screen issue might be a potential parameter that affects the tested data, results from each experimental run can produce certain degrees of indication in terms of filtration, ripening, backwash, etc. Runs, V10-1, V10-4, and V10-5, and runs, V12-1 to V12-3, were based on PVDF screens while runs, T13-1, T13-5, and T13-6, were based on Teflon screens, and runs, D12-1 to D12-3, were based on thick polyester screens. Data of the above runs were listed in Table 10. Note that runs, D12-1 to D12-3, were tested on the RFRF unit with Mil-Spec 12 filter media.

Overall performance of the RFFF filter unit in terms of >2 μm particle removal over different filter media, Mil-Spec 10, 12, and 13 were 91.1% ± 2.58%, 98.3 ± 0.61%, and 96.9% ± 2.26%, respectively, while 98.3% ± 0.27% on the RFRF filter unit on Mil-Spec 12 filter media. Results from the RFRF unit showed the same particle removals to those of runs of the RFFF based on the same filter media, but the standard deviation was much less, which means the RFRF unit achieve better filtration consistency. However, filter capacity was reduced as compared to the RFFF runs (see Table 10).

Less particle removal on runs with Mil-Spec 13 filter media than runs with Mil-Spec 12 filter media might be attributed to screen issues, in which each individual screen of the same material might act differently, and different material screen's sieve opening and uniformity were definitely causing those significant differences though experimental runs. PVDF screens seem to be superior on runs with Mil-Spec 12 media, but no similar findings were observed on runs with Mil-Spec 10 filter media. As screen issue was later resolved by using the thick polyester material, attempts to reveal this phenomenon was not implemented.

Table 10. Summary of operational conditions on runs conducted with three kinds of filter media, Mil-Spec 10, 12, and 13.

Run	Media (Mil-Spec)[a]	Initial flow rate (m/hr)	Initial pressure (kPa)	Ripening time (min)	Run time (min)	Treated volume (m^3)	Percentage backwash over treated volume	Influent turbidity (NTU) Median	Effluent turbidity (NTU) Median	Influent particle counts (>2 μm)/mL Median	Effluent particle counts (>2 μm)/mL Median	Percentage particle removal (>2 μm) Median
V10-1	10	17.5	114	11	89	4.59	3.46	1.5	0.23	15129	1161	92.5
V10-4	10	12.5	73	33	114	4.56	3.32	1.6	0.28	14936	1566	92.7
V10-5	10	12.5	73	44	348	12.95	1.11	0.77	0.18	8334	1038	88.1
V12-1	12	14	86	2	264	11.80	1.35	1.3	0.08	15171	156	99
V12-2	12	15	97	8	168	8.09	2.25	1.4	0.08	15650	321	97.8
V12-3	12	17	117	10	138[b]	7.70[b]	2.16[c]	1.3	0.08	15193	282	98.1
T13-1	13	15	128	39	134	5.95	2.67	1	0.14	10996	409	96.9
T13-5	13	19	186	35	170	3.61	4.19	0.78	0.15	6638	535	94.6
T13-6	13	19	208	14	196	4.22	3.41	0.39	0.1	3074	108	99.1
D12-1	12	16	296	123	175	4.78	3.33	1.2	0.18	6129	300	98.6
D12-2	12	16	286	71	147	3.40	4.23	1.9	0.15	9405	232	98.1
D12-3	12	16	198	42	181	4.53	3.26	2	0.15	9833	190	98.1

Note that Filter media, Mil-Spec10 and 12, was tested on PVDF screens, and Mil-Spec 13 filter media was used on Teflon screens, and thick polyester screens were used with Mil-Spec 12 filter media on reverse-fluidized filter runs. Detailed data of the following runs can be seen in the Appendix D.

[a] Military-Grade glass beads. Specification of size corresponding to numbers of Mil-Spec can be seen in Table 4.

[b] System run was turned off earlier than the usually 420 kPa (60 psi) pressure drop point. As a result, system run time and treated water volume were expected to be greater

[c] Value should be smaller due to greater treated water volume.

Filter capacity was affected by flow rate, particle loading, filter ripening time, and filter particle removal performance. Higher flow rates tended to increase initial pressure, which resulted in longer ripening time and followed a shorter system run time. Increased particle loading had no effect on filter particle removal, but did affect the ripening time. As a result, conclusion on filter capacity must be cautious. Attempts to use total amount of removed particle per run by multiplying treated water volume, percentage particle removal, and particle loading did not provide an absolute index on filter capacity because ripening time varies from run to run and from screen to screen. Screen issue did effect the ripening time, and if screens tended to be relatively easy to be blocked, ripening time was reduced. In some cases, reduced ripening time by blockage of particles and filter media resulted in high pressure drops that exhausted the system run quickly. This kind of phenomena can be seen in the runs, 10-1 to 10-4, on the Table 7 in the preliminary result section.

In order to reduce the initial pressure on the RFRF unit, which was assumed to be the potential factor that results in longer ripening time as compared to those of the RFFF, Run D12-3 was conducted with a split-flow effluent fitting, which reduces the initial pressure to 210 kPa (30 psi) from 280 kPa (40 psi). Percentage particle removals over runs, D12-3 and 12-3, were very similar, but the ripening time of run D12-3 was almost half of that of run D12-2, which resulted in longer system run time and increased treated water volume (see Figure 33).

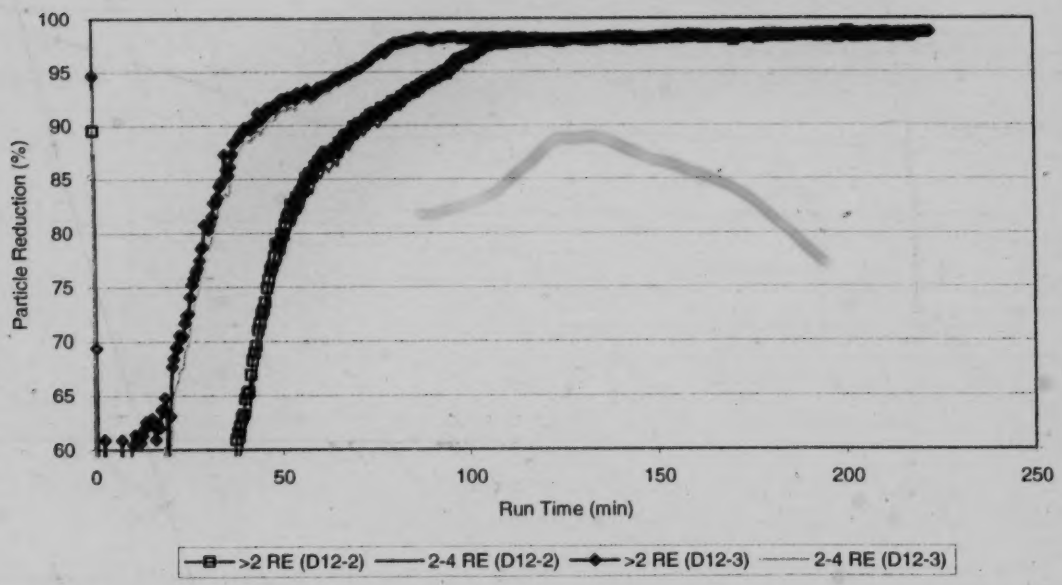


Figure 33. Percent particle removal over time on Mil-Spec 12 media on the RFRF unit with initial flow rate of 16 m/h.

Note that D12-2 indicated second run of RFRF unit with Mil-Spec 12 media. Different factor of the two runs: 70 kPa (10 psi) initial pressure caused by effluent pressure regulator.

6.2. Filter Challenge

Initial attempt of spore removal by calculating the difference in between stock spore concentration and filter effluent spore concentration yielded unexpected results, in which spore enumeration has sometimes turned out to be zero due to low spore concentration of the effluent. Two possible factors that might attribute to the zero count were background loss through the system and membrane loss through spore filtration. The former one might have been caused by spore absorption and the latter one might have been caused by sieve opening as the size of narrow side of *B. subtilis* spores was close to 0.45 μm. Background loss study based on each individual system part revealed that spore losses through the whole system accumulated from spore stock solution, injection tubes, system fittings, delivery piping, etc (see Table 12). Spore loss before the filtration process indicated almost one log loss. This was significantly different compared to the study by Huck et al. (2002) that found < 0.10 log of *B. subtilis* spore loss through the pilot plant apparatus. The system layout and materials used in the apparatus may attribute to this difference. Comparison of 0.22 and 0.45 μm Gelman membranes for *B. subtilis* spore filtration showed no significant difference on ANOVA with 95% confidence. As a result, 0.45 μm Gelman membrane was used thereafter.

Following the background studies, log *B. subtilis* spore reduction by filtration was differentiated between effluent and influent log spore removals. The effluent log spore removal was differentiated between spore log removals of the centrifuge pump point and the filter effluent point while the influent log spore removal was in between the spore log removals of the centrifuge pump point and the filter influent point. Please note that there was no coagulation or any particle destabilization process prior to this direct filtration seeded with *B. subtilis* spores. Table 11 shows the data of five runs, in which BS12-1 and BS12-2 were on Mil-Spec 12 filter media, and BS13-1 to BS13-3 were on Mil-Spec 13 filter media.

Table 11. Summary of operational conditions in filter challenge test on the RFFF unit.

Run	Initial flow rate (m/hr)	Initial pressure (kPa)	Influent turbidity (NTU) Median	Effluent turbidity (NTU) Median	Influent particle counts (>2 μm)/mL Median	Effluent particle counts (>2 μm)/mL Median	Percentage particle removal (>2 μm) Median	System log spore removal	Filter log spore removal*
BS12-1	16	120	1.9	0.15	9024	199	98	0.08	1.2
BS12-2	16	110	2	0.15	8852	140	98.6	0.07	1.1
BS13-1	16	149	1.8	0.15	7330	94	98.8	0.06	1.6
BS13-2	18	182	1.6	0.15	6964	89	98.9	0.1	1.5
BS13-3	19	204	1.5	0.15	7063	87	98.9	0.06	1.5

* Value was differentiated from total log spore and system log spore removals.

Note that Teflon screens were used on all inside and outside cylinders on all runs. Spore loading rate was 20 spores/mL on all runs. System log spore removal presents loss of spore through the systematic parts except filter unit, which substrates from the total log removal to be the filter log spore removal.

Overall log spore removals on Mil-Spec 12 and Mil-Spec 13 media were 1.2 ±0.06 and 1.6 ±0.07, respectively. Due to the low standard deviation, the importance of repeatability of those runs demonstrates the consistency of the RFFF unit in *B. subtilis* spore reduction. The relationship in between *B. subtilis* spore removal and *Giardia* spp. *and Cryptosporidium* spp. removals could not be revealed due to no experimental testing on *Giardia* spp. *and Cryptosporidium* spp. removals. However, based on literature reviews, Hijnen (2000) demonstrated 2 log removal of protozoan (oo)cysts on rapid sand filtration, which was a little higher than 1.7 log removal of *B. subtilis* spores, in the Netherlands. Hijnen (2000) also indicated that *B. subtilis* spore can be regarded as a potential surrogate for protozoan (oo)cysts when the removal efficiency for the spores is similar or to some extent lower than the removal of (oo)cysts. LeChevallier and Norton observed that a one log removal of particles and turbidity corresponding to a 0.66 and 0.89 removal of cysts and oo(cyst), respectively.

For *Giardia* spp. cysts, several investigations have demonstrated little (<1 log) to no removal by sand and dual-media filters (Al-Ani et al, 1986), and tri-media filters (Horn et al, 1988) during no-coagulation conditions. As a result, the log spore removal might be increased if the filtration process were under optimal coagulation.

Figure 34 presents log spore, log particle, and log turbidity removals over time on Mil-Spec 12 filter media while Figure 36 shows those on Mil-Spec 13 filter media. Values of log spore and log particle removals over time were plotted as horizontal and vertical axis for the correlation study, respectively. Apparently, there was no correlation in between log spore and log particle removals shown in Figure 35 and Figure 37 on Mil-Spec 12 and Mil-Spec 13 filter media, respectively.

Table 12. Background loss based on individual system part through the filtration system.

System part	Spore seeding[a]	Stock mixing tank	Injection fitting	Filter influent	Filter effluent by pass	Filter effluent through the RFFF
Log spore loss	0	0.78	0.16	0.12	0.38[b]	1.63[c]

[a] Seeding *B. subtilis* spore concentration was 6.04×10^4 spores/mL.
[b] Filter media was not fluidized to reveal the background spore loss though the RFFF unit.
[c] the value was cited from the run BS13-1 (see Table 11).

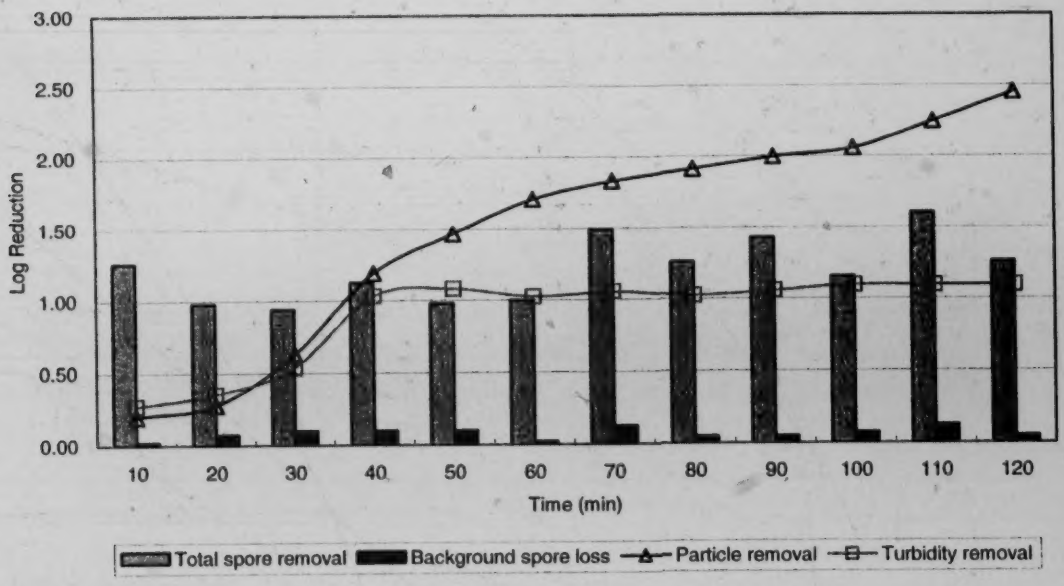


Figure 34. *B. subtilis* spore, particle, and turbidity removals over time on Mil-Spec 12 filter media.

Note that Log reduction from initial 2,000 spores/100 mL.

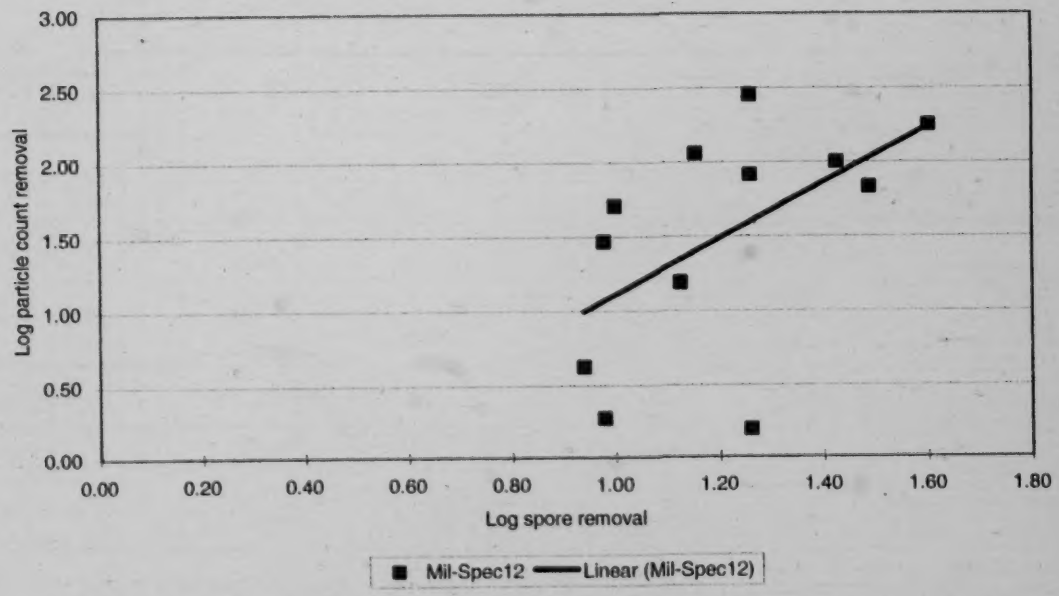


Figure 35. Correlation of particle and spore removals on Mil-Spec 12 media.

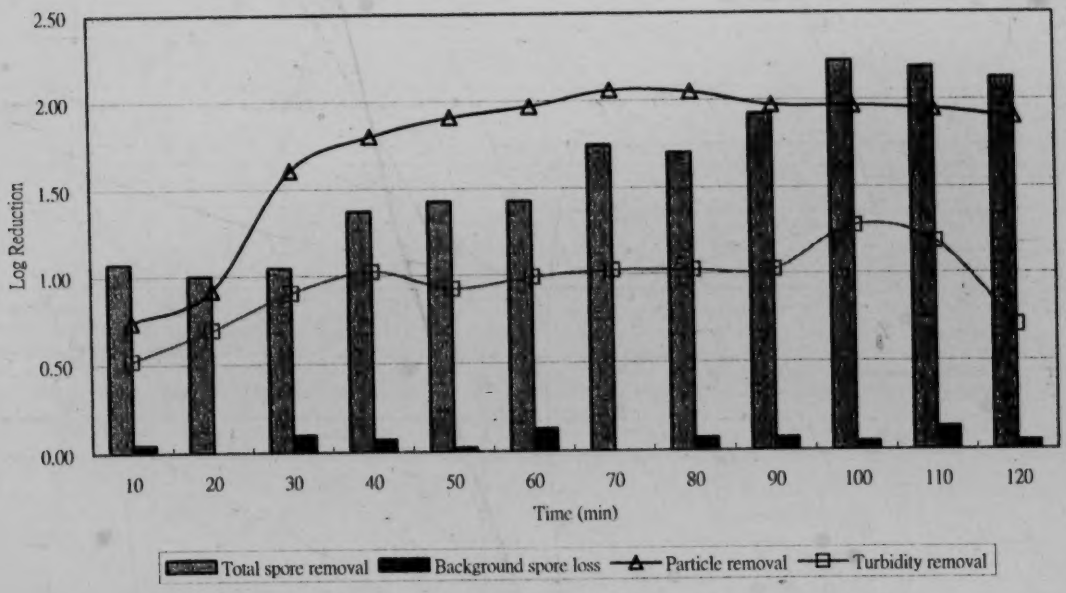


Figure 36. *B. subtilis* spore, particle, and turbidity removals over time on Mil-Spec 13 filter media.

Note that Log reduction from initial 2,000 spores/100 mL.

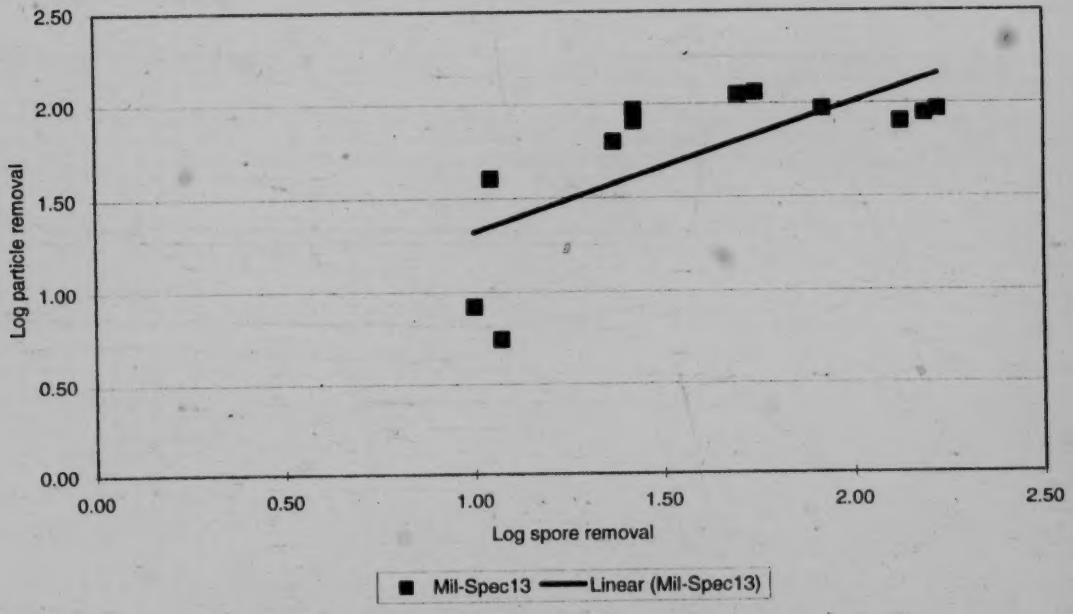


Figure 37. Correlation of particle and spore removals on Mil-Spec 13 media.

6.3. On-Site Pilot Plant Tests

Since water source qualities of raw (RW), filter influent (C3), and clarified effluent (C1 and C2 combined) change from time to time very quickly, it was not possible to control them in the ranges that would eliminate numerous experimental variations. Plus, chemical dosages by the water treatment plant were unknown as were the residuals from the clarifier C1, C2, or C3. The only two quality measurements that this project relied on were the influent particle counts and turbidity. Sieve opening, 33 μm, polyester screens were used on all Mil-Spec 12 and Mil-Spec 13 runs while 105 μm sieve opening polyester screens were used for the Mil-Spec 8 media. Table 13 shows the runs in the on-site pilot plant of the E.L. Smith WTP.

Obviously, percentage particle removal (>2 μm) of the RFRF unit out-performs the RFFF unit in both raw and C3 water sources. This finding differed from that in the Laboratory-based tests, and the reason were attributed to the less fluctuated flow and pressure caused by the centrifuge pump. Particle removal (>2 μm, and 2 to 4 μm) over time on run OF13-1 and OD13-1 can be seen in the Figure 38 and Figure 39. Both runs follow similar trend (e.g. decrease and then recover gradually), but run OD13-1 showed recovery more quickly than run DF13-1. Plus, all of the tests of the RFRF unit did not show spikes occur in the particle removal during filtration.

Backwash water volume used was independent of the treated water volume, but dependent to the numbers of backwash cycles. As a result, longer filtration run time based on low particle loading yields very low backwash percentage over treated water volume (e.g. run OD13-2) while high particle loading exhausted filtration performance more quickly, which resulted in very high backwash percentage of the treated water volume (e.g. run OF12-2). Application of clarified water with low particle counts (e.g. <5000 counts/mL) fell on smaller filter media while larger filter media was used on raw water or clarified water with high particle counts.

Table 13. Summary of operational conditions on runs conducted with two kinds of filter media, Mil-Spec 12, and 13 on both the RFFF and the RFRF filter unit.

Run	Source water	Initial flow rate (m/hr)	Initial pressure (kPa)	Run time (min)	Treated volume (m^3)	Percentage backwash over treated volume	Influent turbidity (NTU) Median	Effluent turbidity (NTU) Median	Influent particle counts (>2 μm)/mL Median	Effluent particle counts (>2 μm)/mL Median	Percentage particle removal (> 2μm) Median
OF12-1	C3	16	185	1238[b]	67.9[c]	0.27[b]	-[a]	0.08	477	163	65.9
OF12-2	Raw	16	183	53	2.04	8.16	-[a]	1.1	18240	4996	73.1
OF13-1	Raw	17	227	92	4.33	4.37	1	0.7	4171	881	79.2
OD 8-1	Raw	16	171	161[b]	9.50[c]	1.67[b]	3.2	2.5	17382	13220	24
OD12-1	Raw	16	245	89[2]	4.79[c]	3.79[b]	1	0.6	3756	652	82.6
OD13-1	Raw	16	335	126	6.29	2.77	0.91	0.45	3377	316	90.9
OD13-2	C3	15	324	1131	42.6	0.39	0.19	0.06	157	20	87.5
OD13-3	C3	15	328	875	35.65	0.49	-[a]	0.16	1375	212	87

Note that OF12-1 means on-site fluidized filter (RFFF) on Mil-Spec 12 filter media while OD12-1 means on-site reverse-fluidized filter (RFRF) on Mil-Spec 12 filter media. Raw means surface water from North Saskatchewan River while C3 indicates the clarified water from the plant's re-carbonate chamber, which was the filter influent going to the plant's deep-bed sand filter.

[a] Data were not recorded due to instrument error.

[b] System run was turned off earlier than the usually 5 m/hr point due to limited time allowance in the E.L. Smith WTP. As a result, system run time and treated water volume were expected to be greater.

[c] Treated water volumes would be greater due to early system shutoff.

[d] Value should be smaller due to greater treated water volume.

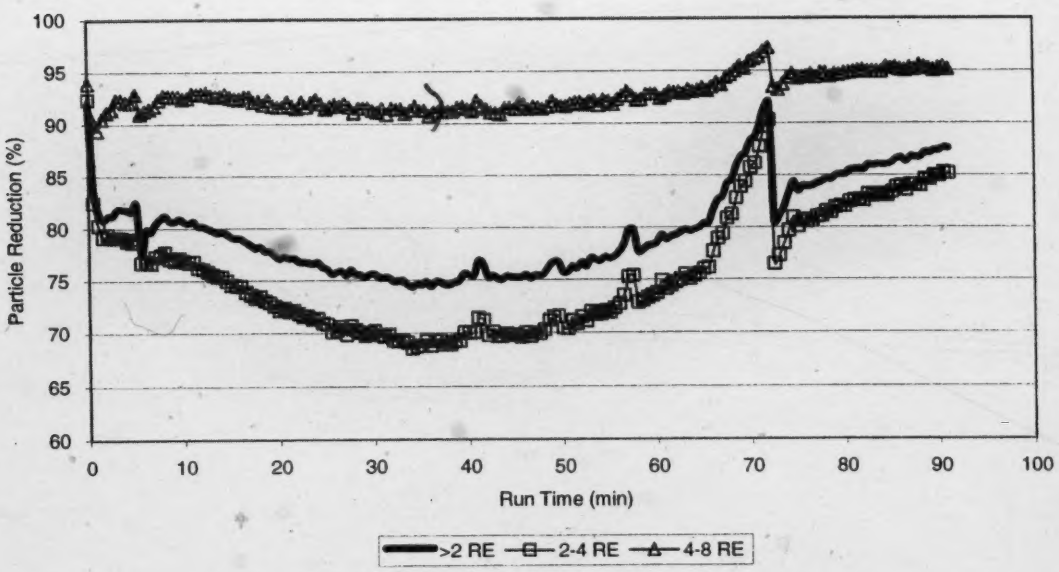


Figure 38. Particle removal over time on Run OF13-1.

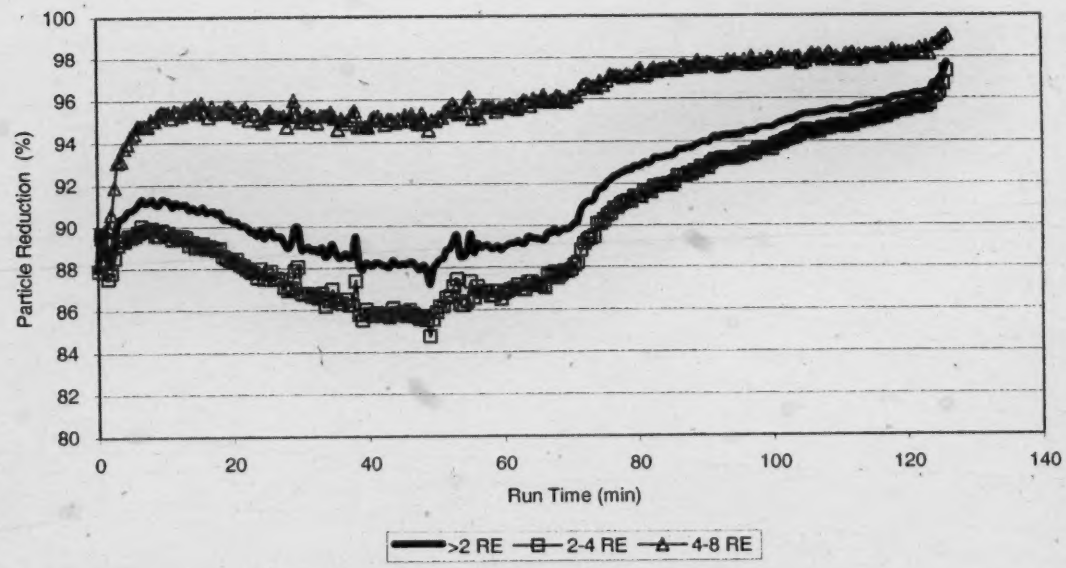


Figure 39. Particle removal over time on Run OD13-1.

Note that run, OF13-1, indicated onsite testing on RFFF unit with Mil-Spec 13 media while run, OD13-1, was onsite testing on RFRF unit with Mil-Spec 13 media.

6.3.1. Impact of Flow Rate on the RFRF Unit

As decreased initial pressure resulted in shortened ripening time, which was found beneficial to the RFFF filter unit in terms of increased filter capacity (see runs D12-2 and D 12-3 on Table 10) particle removal efficiencies were similar. However, runs of the RFRF unit on-site did not have the ripening curves observed in the laboratory-based study. Therefore, an attempt to see if initial flow rate had any impact on filter performance was conducted on the same day in the E.L. Smith WTP to minimize the effect of fluctuated water quality. Data can be seen in Table 14.

Through signal-factor ANOVA test on those three runs, it was found that the flow rate does have an impact on filter's performance, but there was no definite conclusion based on those three runs. Besides, other factors such as source water quality, degree of screen cleanness, etc. might have also attributed to this ANOVA rejection. Therefore, flow rate was selected at 16 m/hr (16GPM) in the rest of the system runs based on the available hydraulic settings at the E.L. Smith WTP.

6.3.2. Sequential Filtration

Filter's performance during the on-site experiments, which was relatively less than that in the lab-based tests, led to another attempt of sequential filtration. This concept was to use relatively large filter media to remove bigger particles and small filter media to remove smaller particles. If low particle effluent water was desired, two cycles of filtration using the same filter media or relatively smaller one can be used. Through two or multiple stages of filtration with the same or different filter media, desired particle removal efficiency can be achieved. Table 15 shows two sets of sequential filtration on the plant's clarified and raw water sources.

Clarified C3 water was fed to the first run with Mil-Spec 13 filter media, OD13-3, which can achieve 92.9% (>2 μm) particle removal, and then the filtrate was collected into two 800 L reservoirs. The filtrate was pumped to the same filter with the same filter media as a second stage filtration. Result of run, OD 13-4, shows 90% (>2 μm) particle removal. By these two sequent filtrations, particle removal (>2 μm) may reach 2 log, which was very close to those of conventional deep-bed sand filters. As this sequential filtration concept proved to be effective, runs, OD8-1 and OD13-5, were tested to treat the plant's raw water source. Results show that 35.9% (>2 μm) on run, OD8-1, and 97.7% (>2 μm) on run, OD13-5.

Table 14. Summary of operational conditions on runs, ID12-1 to ID12-3, conducted with three flow rates, 16, 12, and 8 m/hr (GPM). Mil-Spec 12 filter media on the RFRF unit.

Run	Media (Mil-Spec)[a]	Source water	Initial flow rate (m/hr)	Initial pressure (kPa)	Run time (min)	Treated volume (m^3)	Influent turbidity (NTU) Median	Effluent turbidity (NTU) Median	Influent particle counts (>2 μm)/mL Median	Effluent particle counts (>2 μm)/mL Median	Percentage particle removal (>2 μm) Median
ID12-1	12	Raw	16	241	32	1.04	3.8	1.6	17908	4966	72.3
ID12-2	12	Raw	12	167	28	0.85	3.8	2	17822	7133	60
ID12-3	12	Raw	8	158	30	0.66	3.8	2	17749	5729	67.8

[a] Military-Grade glass beads. Specification of size corresponding to numbers of Mil-Spec can be seen in Table 4.

Table 15. Summary of operational conditions of two sets of sequent filtrations.

Run	Media (Mil-Spec)[a]	Source water	Initial flow rate m/hr	Influent turbidity (NTU) Median	Effluent turbidity (NTU) Median	Influent particle counts (>2 μm)/mL Median	Effluent particle counts (>2 μm)/mL Median	Percentage particle removal (>2 μm) Median
OD13-4	13	C3	15	0.2	0.18	660	46	92.9
OD13-5	13	Filtrate	13	0.2	0.18	164	16	90
OD 8-2	8	Raw	17	2.1	1	19580	12586	35.9
OD13-6	13	Filtrate	13	0.64	0.16	6733	151	97.7

[a] Military-Grade glass beads. Specification of size corresponding to numbers of Mil-Spec can be seen in Table 4.

6.3.3. Smaller Filter Media

Other than sequential filtration, another approach to achieve low effluent particle counts was to use smaller filter media than Mil-Spec 13 media. Three kinds of glass media, N-Mil-Spec 13, Mil-Spec 15, and Mil-Spec 20, were received from John Martin Company. Size distributions of those filter media were not well known, but it was indicated by the company that N-Mil-Spec 13 media had more uniform size distribution than Mil-Spec 13 media, and Mil-Spec 15 media was smaller than Mil-Spec 13 while Mil-Spec 20 media was smaller than Mil-Spec 15. Similar thick polyester material screens with smaller sieve openings were used to contain Mil-Spec 15 and Mil-Spec 20 media while normal thick polyester screens were used on N-Mil-Spec 13 media. Data of runs can be seen in the Table 16.

Except for run, OD20-1, all runs have severe spike occurrences of low particle removal efficiencies during filtration, which leads to the conclusion that using more uniform filter media was not suitable for the RFRF unit. The effluent particle values and the resulting spikes can be seen in the Appendix E. Figure 40 showed the comparison of particle removal curves on runs, ODN13-2 and OD20-1. Apparently, run, OD20-1, had a relatively smooth curve compared to run, ODN13-2. The more uniform filter media, N-Mil-Spec 13, did not outperform the normal Mil-Spec 13 media.

Overall particle removal (> 2 μm) on Run, OD20-1, was 95.2%, which was higher than 92.9% of run OD13-4, on clarified water C3 on the same day. This did indicate that the smaller filter media achieved better particle removal efficiency. Filter media loss observed from run, OD15-1, suggested that the screens used on Mil-Spec 15 media did not contain the media properly; therefore, either smaller sieve opening screens or better screen sealing should be used to correct the problem.

Table 16. Summary of operational conditions of runs using tighter and smaller filter media.

Run	Source water	Initial flow rate (m/hr)	Initial pressure (kPa)	Run time (min)	Treated volume (m^3)	Spike occurs	Percentage backwash over treated volume	Influent turbidity (NTU) Median	Effluent turbidity (NTU) Median	Influent particle counts #[c]/mL Median	Effluent particle counts #[c]/mL Median	Percentage particle removal (>2 µm) Median
ODN13-1	Raw	16.5	299	46[a]	2.46[b]	Yes	6.45	1.5	1	4108	1337	64.1
ODN13-2	C3	16	273	779	32.39	Yes	0.56	0.25	0.19	156	29	81
OD 15-1	C3	8.5	526	270	6.30	Yes	2.76	0.23	0.22	685	156	77.4
OD 20-1	C3	7.5	482	220	4.60	No	3.62	0.22	0.18	702	28	95.2

[a] System run was turned off due to poor filter performance. As a result, system run time and treated water volume were expected to be greater.

[b] Treated water volumes would be greater due to early system shutoff.

[c] Represents the amount of particles (>2 µm)/mL.

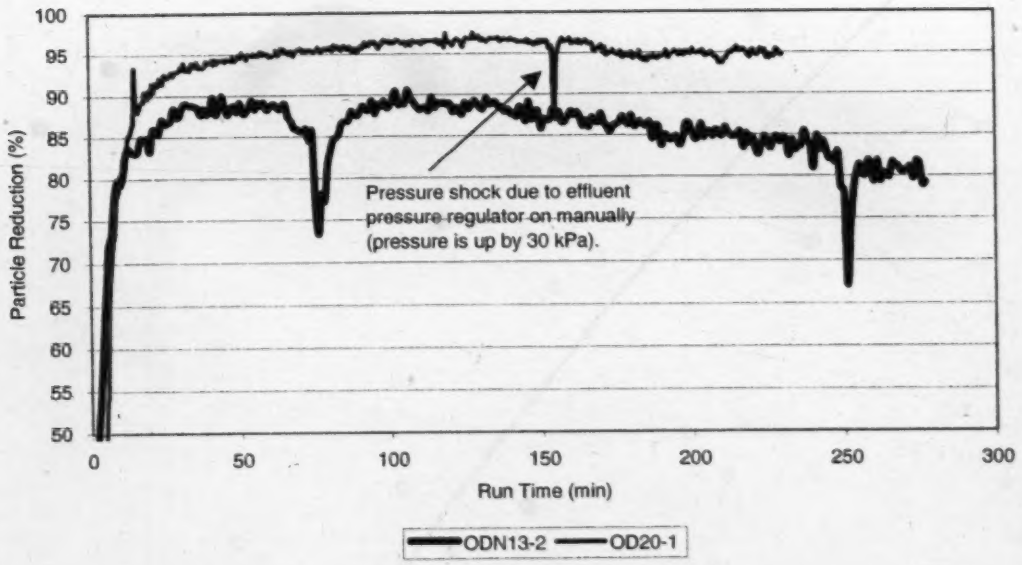


Figure 40. Comparison of two runs with spike occurred on run, ODN13-2, and smooth curve on run, OD20-1.

Note that run, ODN13-2, indicated onsite testing on RFRF unit with New Mil-Spec 13 media while run, OD20-1, was onsite testing on RFRF unit with smaller Mil-Spec 20 media.

6.4. Polymer-added Filtration (in Spring Runoff Period)

Raw water quality in the North Saskatchewan River deteriorated during the Spring break-up period in April. The E.L. Smith WTP adjusted their operational conditions and chemical dosages according to the deteriorated water quality. Particle count (>2 μm) has jumped to 20,000 counts/mL or out of range from the normal 4000 counts/mL range while turbidity rose to several hundred NTU from the normal range of 3 NTU. Due to this significant change of water quality, particle distributions from natural surface water, clarified water, and additions of chemicals were not well known. Note that particle count meter is relatively accurate when the numbers of particle counts are less than the maximum range (Bridgeman et al, 2002).

Since polymer dosage was dependant to the water quality, higher particle counts should have higher dosage of polymer added. However, there was no explicit experiment to reveal the optimal dosage of this particular type of filter-aid polymer, LT-7996, on radial filter unit. The preliminary polymer pump shutoff tests found that 2 mg/L of LT-7996 in 1000 counts/mL (>2 μm) raw water yielded the best result. Note that particle count parameter was not the absolute index to decide the dosage of polymer.

Table 17 presents the data of runs during the spring runoff at the E.L. Smith WTP. Significantly improved filter performance in terms of particle removal was up to 46.5% from 5.75% on runs OD8-5 and OD8-4, respectively. Polymer addition did have an impact on filtration. This can be explained by particle destabilization as polymer carries the opposite surface charge of many natural particles; plus, interparticle bridging also attribute to the pinpoint floc formation. As dosage was doubled in the run, OD8-6, no significant increase in particle removal over the previous run was observed. As the cost of polymer was much higher than alum salt, adding high dosage of polymer was just not practical. Therefore, attempt of seeking the optimal dosage during the spring runoff was ceased.

One interesting finding after run, OD8-6, was that without addition of polymer runs, OD8-7 to OD8-9, have yielded significant particle removal, 98.1%, 89.9%, 71.6%, respectively on clarified water sources. The surprising 98.1% particle removal observed in run, OD8-7, can be explained by the following two factors. First, inadequate cleaning may have left a thin layer of polymer on the screens and grains of the filter media. The deposits of solids near the screen surface of the media break into pieces during normal backwashing, resulting in spherical-shaped accretions referred to as mudballs. Secondly, formation of mudballs was accentuated by the use of polymers as filter aids that form stronger attachments between the filter grains and the removed solids. By applying air souring to clean the dirty filters stated above on runs, OD8-8 and DO8-9, we found that the particle removals were decreased as a result of relative effectiveness of cleaning the screens.

The other interesting finding was that particle counts measured by the influent instrument were higher than the readings in the plant. During the spring runoff, deteriorated water quality brought excessive dosages of coagulants into the clarifiers. The chemicals reacted with particles and microorganisms to form the weak flocs, which were not easy to settle in the clarifiers. Those flocs were later broken to smaller pieces by the intensive shear forces of the centrifuge pump that delivered the clarified water into the RFRF system. Two runs, OD8-7 and OD8-8, were tested in two subsequent days with the same water source (C1 and C2), and the particle (> 2 μm) counts were much greater than those measured by the plant, but gradually decrease to the ranges, which were close to the plant's particle counts as flow decreased below 7 m/hr (see Figure 41). On the contrary, three runs, OD8-4 to OD8-6, based on raw water did not have the trend stated above on clarified water, and the gradually increased particle counts over time were caused by the poor water quality during spring runoff (see Figure 42). Note that the raw water source was directly taken to the pilot plant site from the North Saskatchewan River without any chemical added.

Table 17. Summary of operational conditions of runs during spring runoff. Polymer added filtration runs were listed on the table to compare with runs without polymer.

Run	Source water	Polymer dosage (mg/L)	Initial flow rate (m/hr)	Initial pressure (kPa)	Run time (min)	Treated volume (m^3)	Percentage backwash over treated volume	Influent turbidity (NTU) Median	Effluent turbidity (NTU) Median	Influent particle counts #[a]/mL Median	Effluent particle counts #[a]/mL Median	Percentage particle removal (> 2μm) Median
OD 8-3	C3	0	16	160	260	12.99	1.40	0.77	0.51	9913	5858	40.2
OD 8-4	Raw	0	16.5	187	98	3.25	5.12	8.9	6.8	24248	22873	5.8
OD 8-5	Raw	2.2	16.5	194	50	1.64	11.54	9	4.7	24122	12894	46.5
OD 8-6	Raw	4.4	16	179	48	1.54	10.32	4.7	2.2	22532	11848	47.4
OD 8-7	C1&2	0	16	194	214	9.97	1.82	0.64	0.14	7900	155	98.1
OD 8-8	C1&2	0	16	191	320	15.86	1.10	0.49	0.15	2282	240	89.9
OD 8-9	C3	0	16	246	331	18.60	0.90	0.92	0.28	12059	3409	72.6

[a] Represents the amount of particles (>2 μm)/mL.

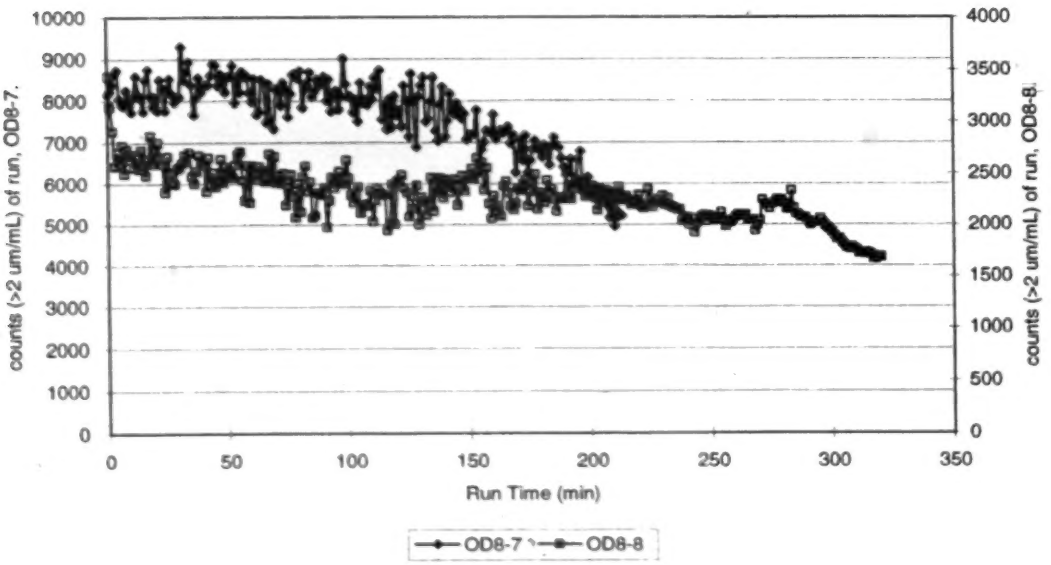


Figure 41. Effect of centrifuge pump on particles. Particle > 2 μm (counts/mL) of runs, OD8-7 and OD8-8, over time.

As flow decreases, lower shear force form centrifuge pump results in less particle counts than those in high flow. Particle (Median counts/mL) measured by the E.L. Smith WTP on runs, OD8-7 and OD8-8, were 4890 and 1550, respectively. Note that runs, OD8-7 and OD8-8 indicated onsite testing on RFFF unit with Mil-Spec 8 media.

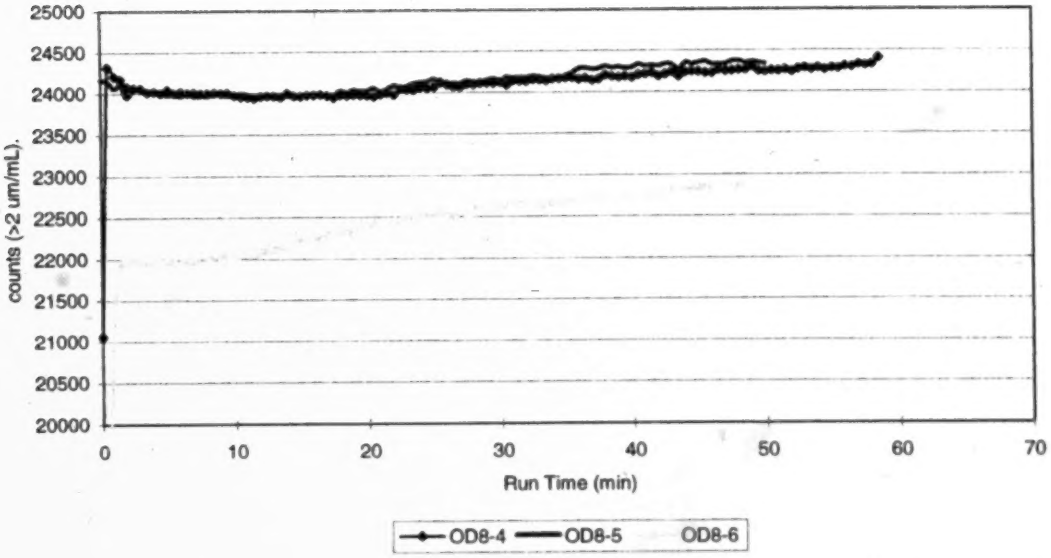


Figure 42. Effect of centrifuge pump on particles in raw water. Particle > 2 μm (counts /mL) of runs, OD8-4 to OD8-6, over time.

Decreased flow does not result in less particle counts than those in high flow. Particle > 2μm (Median counts /mL) measured by the E.L. Smith WTP on runs, OD8-4 to OD8-6, were 23,000, 22500, and 21400, respectively.

7. DISCUSSION

Three issues are addressed in this section; operational parameters, limitations of equipment, and particle destabilization. Secondly, the results and hypothesises would be discussed.

7.1. Three Issues

7.1.1. Operational Parameters:

The experimental parameters investigated during the study were: media size, screen type and screen sieve size, unit flow rate, and particle loading. Some parameters other than those were not well known such as water quality, chemical concentrations in water sources, etc. Therefore, they were included by trial and error of ongoing experiments.

Certain filter media has specific porosity that restricts water flow and allows particular matters to be deposited during filtration. Smaller filter media has less porosity area than that of larger filter media. As a result, better filter performance in terms of particle removal, less filter capacity in terms of treated water volume, and greater pressure increase over time of smaller filter media were expected. Both the RFFF and the RFRF units had similar particle removal efficiency on certain filter media, and their particle removal efficiency increased as smaller filter media were used. When filter media could not be cleaned by backwashing due to the filter's design, both the RFFF and the RFRF units had increased particle removal efficiency and decreased volume of filtrate. This can be explained by the decreased size of sieve opening on the screens by mudballs and small impurities (see Figure 43).

Figure 43. Thick polyester screen was blocked by impurities and filter media after backwashing (HITACHI S-2500).

Higher flow rates tend to increase the pressure drop across filter media, and the elevated shear force might break up the particles attached to the filter media. This results in lower filter performance due to breakthrough. This phenomenon was seen in those RFFF unit runs, in which particle removal tends to be more efficient as decreased flow rate allows particular matter to form cake at the surface of filter media. For the RFRF unit, flow rate seems to be less significant as compared to other factors. This can be explained by that the limited range of flow rate tested in our experiment did not challenge the RFRF unit.

As spaces of filter media were decreased gradually by particulate matter during filtration, pressure was increased over time as a result of less available void spaces in the filter for water flow. Therefore, an indication of a certain pressure increase over system run to signify the filter exhaustion was reasonable. Particle injection

rate did not affect the performance of either the RFFF or the RFRF units in terms of particle removal, but both the filter ripening and system run time can be shortened by higher particle loading rates. Reducing ripening time was a good practice that allows filter to achieve better performance in terms of operational cost. As sieve openings of screens cannot be cleaned completely by backwashing techniques, ripening time was decreased significantly because less screen openings were available for the flow to pass through.

Volume of wasted water by backwash was dependant to the number of backwashing cycles, which was affected by the size of filter media and type of screens, but was independent to the volume of filtrate and the rate of particle loadings. Therefore, the lower the rate of particle loading (e.g. good quality of water source) the less the percentage of backwash water required (e.g. 0.3%).

7.1.2. Limitation of Equipment

Fluctuated flow patterns caused by the centrifuge pump affected the performance of radial flow filter unit in terms of particle removals. The maximum operational pump pressure might have been too low to challenge the radial flow filter unit as no breakthrough was been observed during filtration after the unit was redesigned in July 2003.

As smaller size range particles, 2 to 8 μm, occupied greater than 95% of the total amount of particles in ISO A2 fine dust simulated water, North Saskatchewan River water, and plant's clarified water sources, it was relatively more important to look at particle removals at those ranges because this was the size range of protozoan (oo)cysts (e.g. *Giardia* spp. and *Cryptosporidium* spp.). Two factors might affect particle removal efficiency of larger size particles. First, particle count meter was relatively accurate on smaller particle ranges, 2 to 12 μm than those greater than 15 μm ranges. Second, smaller particles tended to aggregate to form relatively large

particles. As a result, in some experimental runs, particle removal efficiencies on larger particle ranges were either less than those of smaller particle ranges or negative.

The particle count meter measured particle numbers of individual assigned bin size, and any smaller than 2 μm size particles would not be measured due to its optical limitation. ISO A2 find dust was well composed of particle size ranges from 1 to 80 μm. 10% of the ISO A2 fine dust was in less than 2 μm size range while the percentage was not known in the on-site water sources due to the limitation of particle count meters. Percentages of the size ranges, 2 to >15 μm, in between ISO A2 fine dust and on-site raw and clarified water sources were similar before spring runoff period when total particle counts of ISO fine dust, raw, and clarified waters were 3074, 3756, and 157, respectively (see Figure 44). Because the treated water volume per run in the on-site testing runs was less than those with the same operational conditions in the lab-based runs, it was assumed that the water sources from on-site study tended to have impurities that attached to the screens and filter media. During spring runoff period, percentage of larger particles increased on both raw and clarified water sources, and the particle removal efficiency of testing runs was significantly less than the ISO A2 fine dust water and on-site water sources (see Figure 44).

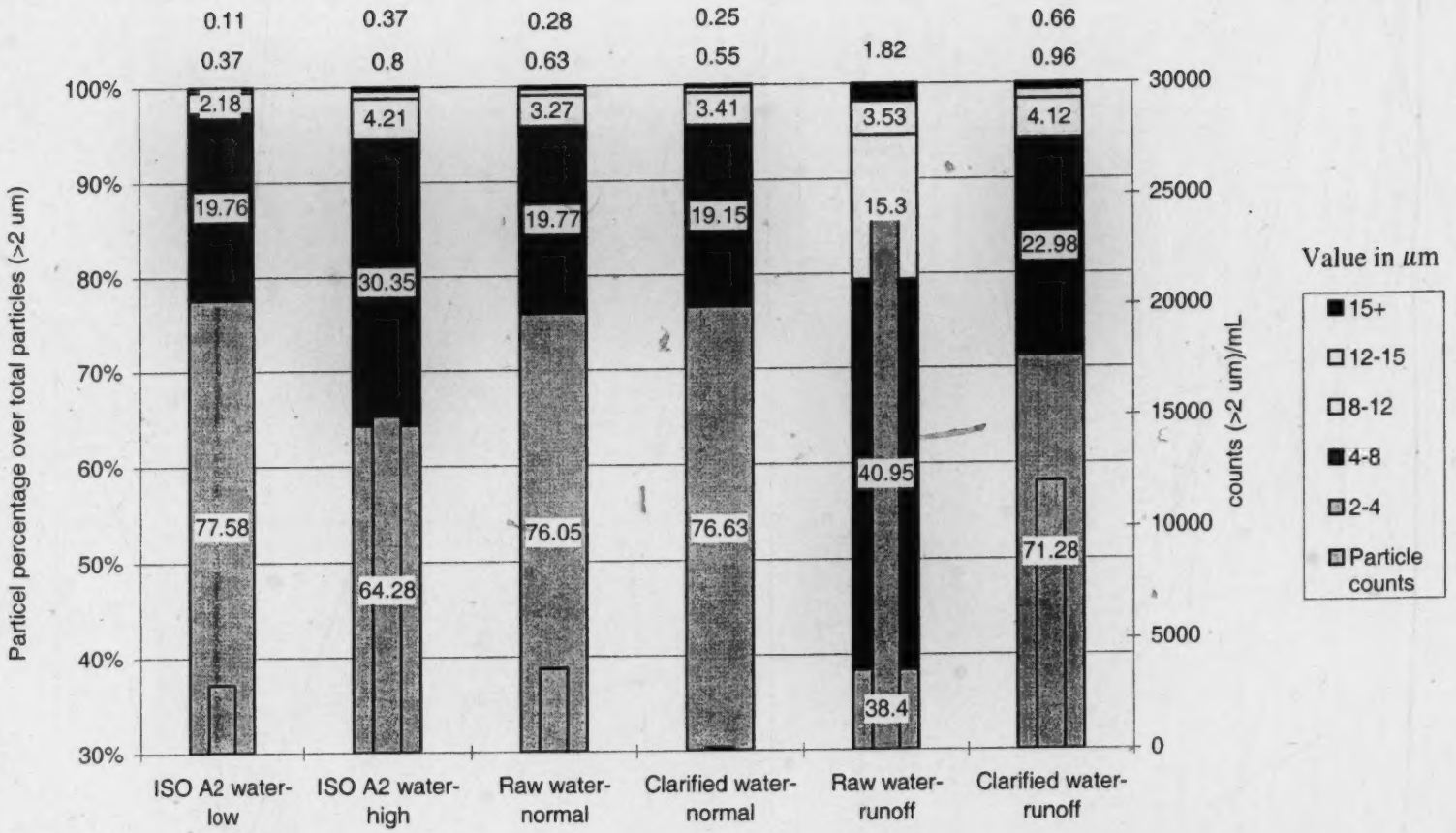


Figure 44. Percentages of the size ranges, 2 to >15 μm, in between ISO A2 fine dust and on-site raw and clarified water sources.

Note that the narrow bars that are inside the percentage bars represent the total influent particle counts (second Y-axis).

7.1.3. Particle Destabilization

As the surface charge of ISO A2 fine dust particles was unknown based on the specification provided by Powder Technology Inc. and the number of particles of tap water was too low to be considered as a factor, destabilization might not be an issue in terms of particle removal during laboratory-based study. During on-site study, both the RFFF and the RFRF units can achieve better particle removal performances of filtration on clarified water over raw water. This phenomenon became more significant as the qualities of water sources deteriorated, especially in the spring runoff period. During this period the plant's clarified water was not well treated even with increased coagulant dosages, and the particle count (>2 μm) was around 15,000 counts/mL. Those particles tended to pass through radial flow filter unit. It can be seen by comparing the percentage of particle removal in between runs before spring runoff and runs in the spring runoff. Radial flow filter's performance was expected to be greater in terms of particle removal with optimized coagulation, flocculation, and sedimentation processes.

As the size of filter media was decreased, straining mechanism was dominant. This condition was similar to those low pressure membrane filtrations, in which the straining mechanism dominated the filtration. On the contrary, injection of filter-aid polymer to the RFRF unit with relatively larger filter media, Mil-Spec 8, did significantly increase the particle removal efficiency on raw water source (see runs, OD8-5 and OD8-6).

7.2. Findings

1. The RFFF unit tested in this study achieved better filter performance than the unit tested by Baxter et al. (2000) using thin polyester screens and Mil-Spec 10 filter

media in terms of particle removal efficiency, filter variance, filter capacity (filtrate volume), filter velocity (flux) rate, and ripening time. The easier to install and change filter parts was another indicator that the redesigned RFFF unit was an improvement.

2. The screen material was an issue regarding the ripening and filtration run times. PVDF and Teflon screens tended to be blocked easily compared to polyester screens, which resulted in decreased ripening time and filtration capacity. Both the RFFF and the RFRF units required ripening time in the range of 15 to 120 minutes on simulated ISO A2 fine dust water depending on several factors such as particle concentration, effectiveness of backwash, etc. However, the ripening time was down to almost zero in all testing runs on both the RFFF and the RFRF units in the E.L. Smith WTP. The difference in between ISO A2 fine dust water and natural raw and clarified water sources may attribute to this finding. The particle removal over time charts were also significantly different on test runs at the laboratory-based and on-site based studies. The laboratory-based and on-site based runs can be found the Appendix D and E, respectively. On the contrary, the twelve due-media deep-bed sand filters in E.L. Smith WTP generally required 30 minutes in ripening, but again there was no direct comparison in between the radial flow filter unit and the plant's filter unit.
3. Experimental tests on ISO A2 fine dust at the laboratory tended to have better particle removal efficiency than those tests done at the pilot plant in the E.L. Smith WTP. ISO A2 fine dust had been found to be a good filtration testing agent because the size distribution was well graded. This eliminated some experimental variants and the results from the laboratory-based tests proved the consistency. Since the water qualities of the plant changed rapidly due to the weather conditions of the North Saskatchewan River, direct comparison in between simulated water by ISO A2 fine dust and the plant's raw and clarified water sources would not be possible. Nevertheless, it was found that the less the particle concentration in the raw water, the closer the particle removal efficiency to that using ISO A2 fine dust. It was also found that the better the particles were destabilized from the clarifiers of the E.L. Smith WTP, the closer the particle removal efficiency was to that using ISO A2

fine dust. In general, if the particle concentration of the plant's raw water and clarified water was around 3,000 counts/mL and 300 counts/mL, the radial flow filter on Mil-Spec 13 filter media could achieve nearly 90% particle removal while nearly 99% on the same filter with similar settings using ISO A2 fine dust. On the other hand, when raw water was deteriorated, clarified water was not well destabilized, and excessive dosages of chemicals were added, particle removal efficiencies of radial flow filter unit were very low.

4. Adding LT-7996 filter-aid polymer was found to be significant in terms of particle removal and shorten ripening time in the plant's raw water compared to no filter-aid polymer added test. The dosage of LT-7996 to the raw water depended on the water quality and since the quality of raw water changed rapidly, optimum dosage experiment was not conducted. Plus, selection of optimum polymer for the radial flow filter unit was also not performed due to limited sources. Nevertheless, cationic type of LT-7997 did help in particle destabilization, build interparticle bridging, etc. to improve the filtration efficiency.
5. Radial flow filter unit was found to require 0.3% to 3% of the produced water for backwash based on throughput volume of filtrate. The lower the rate of particle loading (e.g. good quality of water source), the less the percentage of water used for backwash. Application of a certain filter media on a certain water source defines the required backwash water because the volume of wasted water by backwash was dependant to the number of backwashing cycles, which was affected by the size of filter media and type of screens, but was independent to the volume of filtrate and the rate of particle loadings. Lower backwash water requirements indicate the cost reduction of filtration.
6. The repeatability of the filter challenge runs with *B. subtilis* spores demonstrated the consistency of the RFFF unit due to the low standard deviation. This indicated that the RFFF unit had the efficiency to reduce the number of pathogens. The relationship in between *B. subtilis* spore removal and *Giardia* spp. *and Cryptosporidium* spp. removals could not be revealed because of no experimental testing on *Giardia* spp. *and Cryptosporidium* spp. removals. Nevertheless, based on the literature review, the removal efficiency for the spores was similar or to

some extent lower than the removal of (oo)cysts. The RFFF unit had slightly less log spore removal compared to some conventional deep-bed sand filters (e.g. 2 logs) can be attributed to no coagulation/ flocculation/ sedimentation processes were performed before the spore filtration tests due to the zeta potential of *B. subtilis* spores that tended to be repulsive to escape. Also, almost one log unit of *B. subtilis* spore loss throughout the system parts from the spore seeding point to the RFFF unit may also lead to an interesting research area as compared to <0.1 log unit loss of *B. subtilis* spores reported by Huck et al, 2000.

7. During the filtration study of radial flow filter unit, four of six effects on particle removal efficiency were found to be similar to the results reported by Letterman (1987). They were listed as follows:
   I. Increased or decreased influent particle concentration resulted in no change on particle removal efficiency.
   II. Increased interstitial velocity (filtration rate) resulted in decreased particle removal efficiency on the RFFF unit while was no change on the RFRF unit. The difference can be attributed to the limited range of velocity (10 to 16 m/h) did not challenge the RFRF unit.
   III. Increased filter pore diameter by using larger filter media resulted in decreased particle removal efficiency while decreased filter pore diameter resulted in increased particle removal efficiency.
   IV. Increased particle attachment efficiency (degree of destabilization) by coagulation/ flocculation/ sedimentation from the E. L. Smith WTP and filter-aid polymer from LT-7996 resulted in increased particle removal efficiency.

The other two of the six effects, particle density and length of the filter pore (depth of the medium) were not performed due to the nature of ISO A2 fine dust and radial flow filter unit.

8. CONCLUSIONS

Four parameters were tested using the radial flow filter units as applied to drinking water treatment, but only the screen type and filter media size were found to be significant parameters in terms of particle removal efficiency. Thick polyester screens worked well when used with media larger than the screen openings. Inconsistent filter performance in terms of particle removal was reduced by redesign of unit parts. The RFFF unit was found to achieve 91.1% ± 2.58%, 98.3 ± 0.61%, and 96.9% ± 2.26%, particle removal over >2 μm on simulated water using ISO A2 fine dust on Mi-Spec 10 (90 to 150 μm), Mil-Spec 12 (50 to100 μm), and Mil-Spec 13 (40 to 90 μm) filter media, respectively. This finding was better than the previous results reported by Baxter et al, 2000.

In the filter challenge test, overall log removals on the RFFF unit with Mil-Spec 13 and Mil-Spec 12 filter media were 1.6 and 1.2, respectively. The relationship in between log spore reduction and particle reduction was poor.

The other Radial Flow Reversed Fluidized Filter (RFRF) unit was later developed by John Martin Company and proved to be superior to the RFFF unit in terms of particle removal efficiency (increased particle removal) and consistency (decreased standard deviation). The particle reduction relationship by the both the RFRF and RFFF units with Mil-Spec 12 and 13 media in between simulated water using ISO A2 fine dust and natural raw water was poor (i.e. Table 10 and Table 13). This relationship became worse when the quality of water sources deteriorated during spring runoff period.

Adding 2.2 mg/L of LT-7996 filter-aid polymer to the raw water was found to significantly improve the particle removal efficiency from 5.75% to 46.5% using the RFRF unit with Mil-Spec 8 filter media during spring runoff.

The sequential filtration study was found to be practical when source water quality was poor. Filter ripening time in the on-site and the laboratory runs was zero and 15 to 120

minutes, respectively. Backwash requirement based on throughput volume was in the range of 0.3% to 3%, which was very much depending on the particle loading.

The low backwash requirement, less ripening time, and minimum space are the major advantages of radial flow fluidized units. Further research on this unique filter unit is needed to reveal the filter's real performance with a wider range of operating conditions.

9. RECOMMANDETIONS FOR FURTHER STUDIES

1. An investigation of using a constant flow pump may be preferable on either the RFFF or the RFRF unit to eliminate the suddenly fluctuated flow and pressure during filtration.
2. A match of the size of thick polyester screens and the size of filter media should be investigated to prevent the screen blockage by the filter media, enhance backwashing, and reduce operational cost.
3. The screen-media relationship should be investigated to optimize filter's performance in terms of particle removal, filter capacity (treated water volume), and low backwash water requirement.
4. A particle destabilization study is recommended as many of natural microbial species carry surface charge. *B. subtilis* spore reduction may be increased with chemical additions (e.g. coagulant, polymer, etc.) due to particle destabilization.
5. Future study of automated controls should be optimized to save operational time and backwash water volume (e.g. manual flow valves can only be adjusted one after another while multiple signal control valves can be controlled at one time).
6. Further research is required to examine the potential of sequential filtration by two or more stages using either the same or different filter media.

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APPENDIX A

Fluidization, Filtration, and Backwash Protocols of The RFFF and RFRF units

A1. The RFFF Unit

Please check Figure 45, Figure 46, and Figure 47 for the referring valve numbers used to represent the specific valve in the RFFF system. Please note that "A" means Air, "PC" means particle, "V" means adjustable valve, "E" means Effluent, "D" means Drain, "T" means Top, and "B" means Bottom.

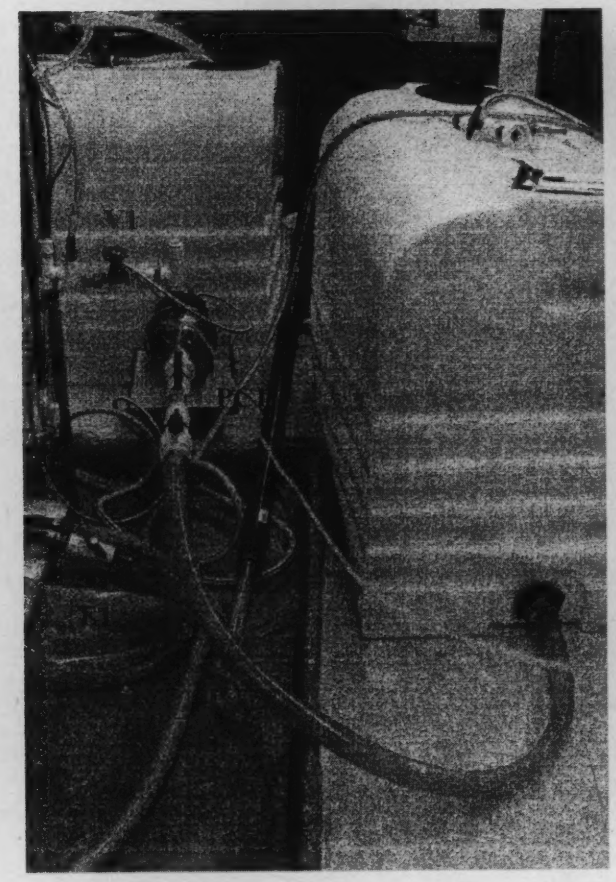


Figure 45. Water influent and effluent control valves with two 800 L reservoirs.

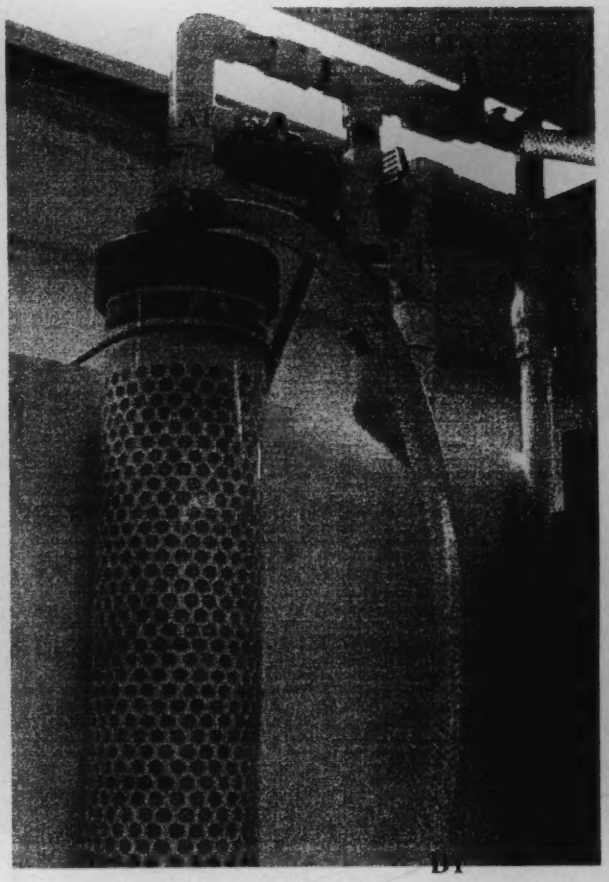


Figure 46. The RFFF effluent control valves.

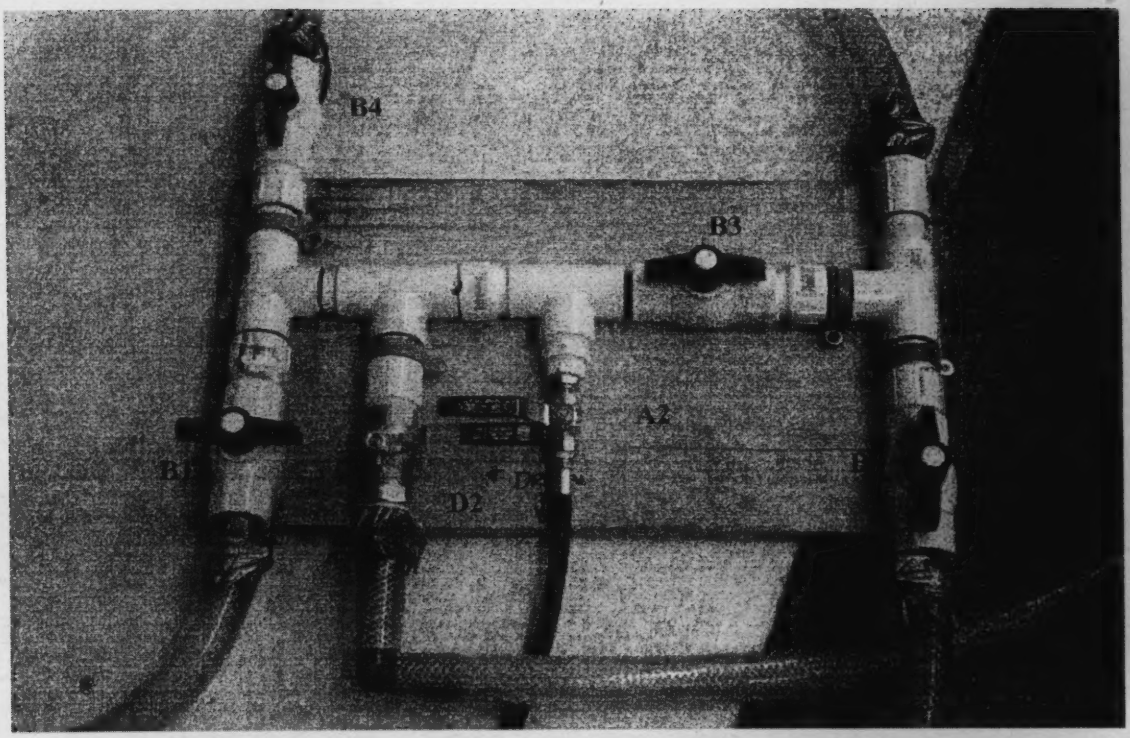


Figure 47. The RFFF bottom valves. Note that line of "B1" valve represents fluidization line while that of "B2" represents filtration line.

A1.1. Fluidization:

Plate valve "V1" was adjusted according to the maximum initial flow rate, and injection valve "PC1" was "ON" only when the data acquisition system was recorded.

	B1	B2	B3	B4	T1	T2	T3	A1	A2	E1	D1	D2
Valve Status	o	x	x	o	x	o	o	x	x	o	x	x

If glass beads form cylinder-like block as being fluidized, apply air scouring at valve "A2" for about 2 min. to stir beads to decrease density so that fluidization water can easily move beads to the upper chamber of the RFFF.

	B1	B2	B3	B4	T1	T2	T3	A1	A2	E1	D1	D2
Valve Status	x	x	x	o	x	o	o	x	o	o	x	x

Maintain fluidization for at least 2 min. to support beads at the proper position and remove trapped air in the RFFF, and then turn on Valve "B3" to split only axial flow to axial and racial flows. The former one was used to continue fluidizing and the latter one was the main filtration path to remove undesired particles. Turn on "B2" and Turn off "B1" in sequences to have water flow through the main stream which has instruments to conduct filter performance experiments.

A1.2. Filtration

	B1	B2	B3	B4	T1	T2	T3	A1	A2	E1	D1	D2
Valve Status	x	o	o	o	x	o	o	x	x	-	x	x

When pressure increases and flow rate decreases as a result of cake formation during filtration, particle injection rate through metering pump was manually adjusted to maintain certain range which was set to suggested level to achieve best result, and valve "E1" was needed to adjust as well; otherwise, there would not be enough flow going into effluent detecting instruments.

After operation for a period of time, the RFFF, in terms of either available pressure increase or turbidity or particle counting limitation, was exhausted and needs Backwashing to renew its filter capacity. It was recommended that this effective Backwashing was essential to long-term successful service of a filter. The aim of the Backwashing operation was to keep the filter acceptably clean, so that no progressive evidence of the development of dirty-filter problems, such as mud balls and filter cracks, occurs.

A1.3. Backwashing

A1.3.1. Turn off flow

	B1	B2	B3	B4	T1	T2	T3	A1	A2	E1	D1	D2
Valve Status	x	x	o	o	x	o	o	x	x	o	x	o

As the system flow was turned off, all the glass beads in the upper chamber during filtration fall down to the lower chamber due to lack of fluidization. Large trapped and cake-form particles were flushed out from the bottom-perforated cylinder, followed with glass beads, while small particles tend to suspend at the top of glass beads. Therefore, grey colour and light brown colour form two distinctive layers at the lower chamber of filter, glass beads and suspended particles, respectively.

A1.3.2. Moving beads down

The following setting was aimed to move all the beads to the lower chamber. There were three purposes of doing this. First, it can be observed that if there were any filter defect, from which glass beads would loose during fluidization, filtration, and backwashing. Second, operators can observe the cleanness of beads to decide how many times of backwashing was needed. Third, using air scouring to remove trapped impurities and undesired particles can be made.

	B1	B2	B3	B4	T1	T2	T3	A1	A2	E1	D1	D2
Valve Status	x	o	x	o	x	x	o	x	x	o	x	o

A1.3.3. Air scouring

Air scouring was introduced to the bottom of filter with 407 kPa (60 psi) for 3 min., whose pressure was set to prevent backflow from mainstream water line and provide enough turbulence to clean beads.

	B1	B2	B3	B4	T1	T2	T3	A1	A2	E1	D1	D2
Valve Status	x	x	x	o	x	o	o	x	o	-	x	x

A1.3.4. Fluidization

The suspended particles after air scouring were flushed out from the top perforated inside and outside cylinders of filter as fluidization water was introduced into the filter. Valve "D1" might be turned ON for 1 min. to further remove particles. Refer fluidization table for Valve settings.

A1.3.5. Repeating

Operation of five cycles of the operations from 1.3.1 to 1.3.4 was standard to 95% completely clean the glass beads in the filter to an acceptably clean to back to filtration. The above operation was called backwashing. Three cycles were needed to keep the filter to an acceptably clean to back to filtration.

A1.4. Cleanness of Beads

Once glass beads were cleaned to back to filtration, two easily physical ways can be made to determine if they were clean; they were the initial pressure reading of filtration and the duration time of system run.

A1.5. Cleanness of screens

Permeability of outer and inner cylinder screens was gradually decreased due to accumulation of fine dust during several system runs, and the above backwashing method was unable to clean those screens effectively. This phenomenon can be observed at the later filter runs as the mainstream pressure builds up significantly when

compared to the initial filter run where the pressure increases gradually. As a result, the following modification of backwashing was needed to accomplish the complete cleanness of both glass beads and fine screens.

Water from backwashing line and air from top inlet "A1" greatly introduce into the inner cylinder with pressure setting at 543 kPa (80 psi) and 407 kPa (60 psi), respectively. The mixed air and water solution flows through inner screen and cylinder space, and out from the outer screen and annular space to drainage. Those trapped fine dust and particular matters were cleaned. This step can be applied after 2 cycles of the above bead backwashing steps.

	B1	B2	B3	B4	T1	T2	T3	A1	A2	E1	D1	D2
Valve Status	x	x	o	o	x	x	x	o	x	o	x	o

A2. The RFRF Unit

Operational steps were very similar to the RFFF filter unit. Please refer to the RFRF unit in section 3, Filter concept description.

APPENDIX B

Calibration of Mixing Intensity versus RPM

Before the velocity gradient itself was discussed, a restatement of the definition of coagulation and flocculation would be appropriate. Coagulation was the process of chemically altering colloids so that they would be able to approach each other and form larger particles. The reactions of coagulation involve: double-layer destabilization, sorption, chemical and enmeshment mechanisms. Flocculation was the physical process of bringing the coagulated particles into contact to promote floc formation.

Without mixing, particles would collide through the natural phenomenon of Brownian motion. The natural settling process of particles was slow and no further collision was available; therefore, mixing coagulated or polymer-aided water or both might be beneficial. The mixing process itself was based on the theory of accelerating the collision of two spherical particles. Detail mathematical models would not be discussed.

Camp developed the following specific relationship for shear along parallel planes of an elemental volume of water:

$$G = \sqrt{\frac{P}{\mu V}} \qquad \text{Equation 3}$$

where P= power input (W); V= volume of water receiving the input (m^3); and μ= dynamic viscosity (Pa.s).

The G value can be used to determine the water power to be applied to a particular volume of water or mixing basin. The actual motor power must be larger than the water power to account for losses through the couplings and gear reducers.

Impellers were divided into two general groups, axial flow and radical flow. The latter one was used in this experiment. The liquid discharges from the impellers at right angles to the axis and along a radius.

Evaluating shear rate can be accomplished by using Equation 3, which relates G to the

water power, and an expression for the power applied to water by an impeller. Rushton et al developed the following relationship for power input under nonvortexing, turbulent conditions:

$P = \phi \rho n^3 D^5$ Equation 4

where P= power input (W); ϕ= impeller power number (unitless); n= impeller speed (rps); D= impeller diameter (m); and ρ= mass density of fluid (kg/m^3).

Combining Equation 3and Equation 4 as follows:

$$G = \left(\frac{\phi n^3 D^5}{vV}\right)^{1/2}$$ Equation 5

where v= kinematic viscosity (m^2/s)

Except for the power number (ϕ), all remaining values were readily available or easily set. Power number was determined experimentally as a function of basin-impeller geometry and Reynold number (R).

A flat-blade radical turbine with six blades was used in this experiment. According to the power curve for flat-blade turbine done by Cornwell D. and Bishop M., they suggested the possible way to evaluate closely by the following procedure:

1. Vortexing must not be present.
2. Select the proper power curve that has geometry most like the full-scale system of interest.
3. Adjust the power number obtained from the curve for geometric differences. The power number was corrected by using the following equation:

$\phi_2 = \phi_1 (Ratio2/Ratio1)^n$ Equation 6

where ϕ_2= corrected power number; ϕ_1= power number obtained from the curve; Ratio2=

dimensionless ratio factor for ϕ_2 system; Ratio1= dimensionless ratio factor for ϕ_1 system.

System measurements were listed as follows into calculation:

ϕ_1 system (curve), ϕ_1= 5, n= 0, D/T= 0.58. ϕ_2 system (real) D/T= 0.16, so

$\phi_2 = 5(0.16/0.58)^0 = 5$

Therefore, applying Equation 5 with the power number ϕ= 5, impeller diameter D= 0.086 m, kinematic viscosity v= 1.004×10^{-6} m^2/s at 20 ^oC, and volume V= 0.15 m3, we have the following equation based on impeller speed only (rps):

$$G = \left(\frac{5n^3D^5}{vV}\right)^{1/2} \quad \text{Equation 7}$$

Figure 49 shows the motor speed versus mixing intensity and Figure 48 presents the calibration of mixing intensity based on motor's speed.

Motor mixing speed through its controller setting versus mixing intensity.

motor setting	0	1	2	3	4	5	6	7	8	9	10
rpm	9	90	180	270	360	450	540	630	720	810	900
rps	0.15	1.5	3	4.5	6	7.5	9	10.5	12	13.5	15
G	0.73	23	65	119	184	257	337	425	520	620	726

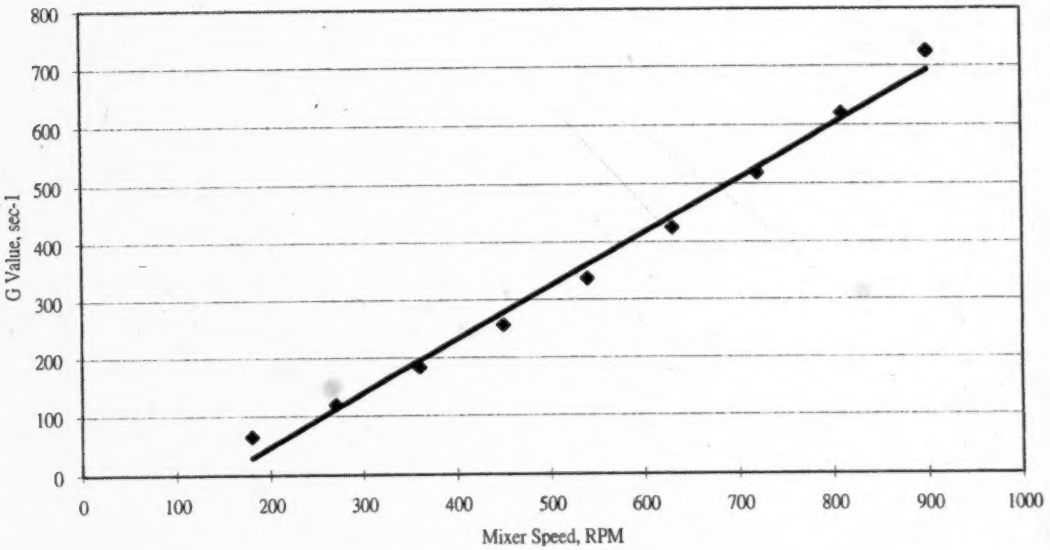


Figure 48. Mixing Intensity "G" Value Calibration Curve for Polymer Mixing Tank

APPENDIX C

Procedures of Spore Preparation, Generation, and Enumeration

C1. Preparation

ELGA Water

1. Turn on machine.
2. Wait until 18.2 Ω was achieved.
3. Fill container with purified water.

AGAR

1. Measure the appropriate amount of R2A Agar powder on plate (18.2 g in 1L ELGA water).
2. Transfer powder to a 4 L Erlenmeyer flask with a stir bar.
3. Measure out the appropriate amount of ELGA water.
4. Add a portion of the required water to the flask and mix vigorously.
5. Add the remaining water, rinsing down the sides of the flask.
6. Stir the mixture on a hotplate (maximum heat setting, and some vortexing) just until the mixture begins to boil. This typically takes 20 to 25 minutes for a 2.5 L batch. Be sure not to let the agar boil vigorously, as it would rapidly boil over and create a major clean up job.

Dilution Water (0.1% Bacto Peptone Solution)

1. Prepare a 10% Bacto Peptone solution (20 g in 200 mL ELGA water).
2. Transfer 40 mL of 10% solution into 4.0 L of ELGA water (large jug was preferable).
3. Use piston-pumping machine to fill required dilution bottles with 90 mL of dilution water.
   a. Check volume of piston pump before, in the middle and at the end of filling bottles (decreasing speed increases volume).
   b. Typical pumping speed was at the 10 setting.
4. Place bottle caps on, a 1/4 turn less than tight.
5. Autoclave for 30 minutes.
6. Remove from autoclave and let cool for 2 to 3 hours before tightening bottle

caps.

Phosphate Buffer

1. Refer to laboratory procedures manual for appropriate quantities of salts to create the desired pH.
2. Measure out the required amounts of Na_2HPO_4 and KH_2PO_4 using a highly accurate scale. (typically make 4 L batches)
3. Place powder in a 4l Erlenmeyer flask with a stir bar.
4. Measure out the appropriate amount of water and use some of this water to rinse the powder out of the measuring dish.
5. Add water and mix on stir plate for approximately 10 to 15 minutes.
6. Check the pH using a pH meter.
7. Record the chemical usage, and measured buffer pH in the lab preparations book.

Tryptic Soy Broth

Typically ½ L batches were made. TSB was used as a nutrient broth for plate pads.

1. Measure out the required amount and add to ELGA water (30 g in 1L ELGA water)
2. Stir and heat (2 to 3 setting on the hotplate) for 15 minutes
3. Pour into 4 separate 250 mL Erlenmeyer flasks and cover with foil
4. Autoclave for 30 minutes

C2. Generation

Inoculating Test Tubes

1. Fill 3 test tubes just over half full with BBL Nutrient Broth.
2. Autoclave tubes for 30 min.
3. Add 1 mL mother stock to 2 test tubes using sterile pipets (3^{rd} one acts as control).
4. Cap all test tubes.
5. Place all 3 tubes in the incubator for 48 hours at 37°C.

(Place tubes on an incline to maximize liquid-air interface, but prevent Leaking)

Growing Spores on Agar

1. Prepare 2.5 L of Agar.
2. Divide the Liquid agar equally between nine 1 L Erlenmeyer flasks (approx. 300 mL each) and cover flask tops with foil.
3. Autoclave agar flasks for 30 min.
4. Add 1 mL of incubated seed solution from test tubes to each bottle.
   (Flame the top of the test tube before use to kill any foreign microorganisms)
5. Add 15 mL of pH 6 buffer solution to each flask.
   (Flame top of Erlenmeyer flask before putting foil back on)
6. Incubate at 37°C for 14 days.

Harvesting Spores

1. Remove flasks from incubator. (Flame flask opening)
2. Drain flasks into 2 plastic, 200 mL centrifuge bottles so both have roughly equal volume. (Flame flask opening)
3. Add approximately 10 mL of pH 6 phosphate buffer to each flask using a sterile pipet
4. Swirl and drain into the same centrifuge bottles. (Flame flask opening)
5. Swirl and drain again to remove any Liquid trapped under the agar.
6. Fill the remaining space in the 2 plastic containers with pH 6 buffer.
7. Centrifuge at 4500 rpm, at 4°C for 15 min.
   (Add water to the test tubes in the centrifuge inserts to ensure the inserts with the bottles inside were of equal weight before starting machine)
8. Dump agar from flask into the garbage and rinse flasks.
9. Remove bottles from centrifuge at end of cycle and drain the supernatants, only leaving the hard pellet at the bottom of the bottle.
10. Add approximately 75 mL of pH 6 buffer to each bottle and mix until the pellet was dissolved.

11. Combine the liquid from both centrifuge bottles into one bottle and fill the remaining volume with pH 6 buffer.
12. Centrifuge at same settings using a centrifuge bottle filled with water to balance the machine.
13. Drain supernatant.
14. Add approximately 75 mL of pH 6 buffer and mix until the pellet was dissolved and fill bottle with pH 6 buffer.
15. Repeat steps 12, 13 and 14.
16. Place bottle in 76°C water bath for 1 hour.
17. Repeat steps 12, 13 and 14.
18. Label bottle as Bacillus Subtitles and also record the date washed and a brief description of the washing procedure (e.g. Washed 3 times in pH 6, phosphate buffer, water bath at 76°C for 1 hour, washed again).
19. Store in fridge.

C3. Stock Enumeration

1. Using a sterile pipet, add 1.5 mL of tryptic soy broth (TSB) solution to each Plates. (can be done before plating begins)
2. Label plates. (control and duplicate)
3. Fill one 75 mL beaker with 95% alcohol to be used to flame forceps for each dose being plated. (including the control)
4. Set up autoclaved filter apparatus.
5. Light bunsen burner.
6. Sterilize forceps by heating to red hot and then quench them in the alcohol.
7. Burn off residual alcohol on forceps and place membrane filter in the filter apparatus.
8. Shake dilution bottle for approximately 10 seconds.
9. Remove cap and flame the mouth of the dilution bottle.
10. Starting with the most dilute sample, turn on the suction and dump the dilution through the filter.
11. Flame the dilution rinse bottle mouth.

12. Pour approximately 75 mL of dilution water into the apparatus to rinse the filter and apparatus.
13. Flame dilution rinse bottle.
14. Burn off residual alcohol on forceps and transfer membrane filter to the appropriate plate.
15. Repeat steps 7 to 14 for each dose, working from weakest to strongest dilution.
16. Place all plates in an oven for 25 minutes at 76 °C.
17. Incubate all pates at 37°C for 24 hours.
18. Count and record the number of spore colonies.

APPENDIX D

Data Generated in the Result Section

Run, V10-1, RFFF_MS10_July19

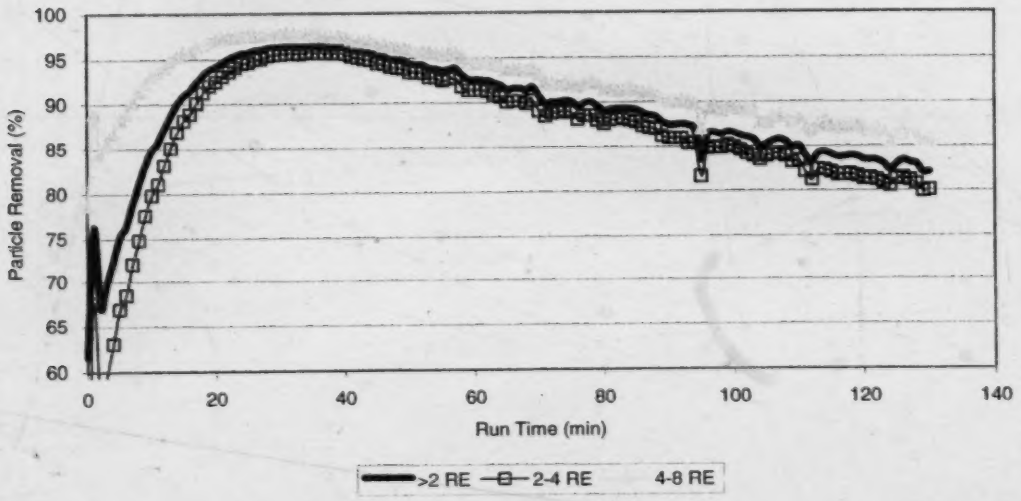
ISO A2 dust influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	764432	491367	231971	32160	6119	2817
Std Dev	36898	20134	14908	2388	720	1002
5th	721560	470599	213436	28952	5450	2306
25th	745217	482877	223751	30606	5731	2452
50th	763138	491414	230855	31794	6020	2648
75th	787063	502516	241360	33481	6350	2821
95th	820518	518566	256334	36590	6946	3336
Bin percentage	-	64.28	30.35	4.21	0.80	0.37

ISO A2 dust effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	75293	58686	14778	1275	255	299
Std Dev	50547	42753	8451	911	191	236
5th	27100	20988	5030	397	83	117
25th	37509	29346	7034	498	110	149
50th	67386	51022	13544	894	187	195
75th	90479	68665	19763	1994	343	355
95th	196213	166312	28743	3131	635	853
Bin percentage	-	77.94	19.63	1.69	0.34	0.40

MS 10_Removal Efficiency (from 85% ripening to 50 psi pressure drop)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	90.21	88.07	93.69	96.10	95.90	89.29
Std Dev	6.58	8.82	3.58	2.67	2.94	8.54
5th	76.20	67.51	88.34	91.15	89.86	65.60
25th	88.41	86.21	91.44	93.93	94.37	87.81
50th	91.57	90.10	94.33	97.09	97.09	92.84
75th	94.86	93.92	96.88	98.35	98.13	94.13
95th	96.33	95.61	97.74	98.72	98.60	95.58
Median	91.57	90.10	94.33	97.09	97.09	92.84
Median (after 85%)	92.46	91.06	95.00	96.70	96.57	93.13

Turbidity	Influent	Effluent
Median	1.4752	0.2295

Percent particle range removal over time on Run, V10-1, RFFF_MS10_July19



Run, V10-4, RFFF_MS10_July24

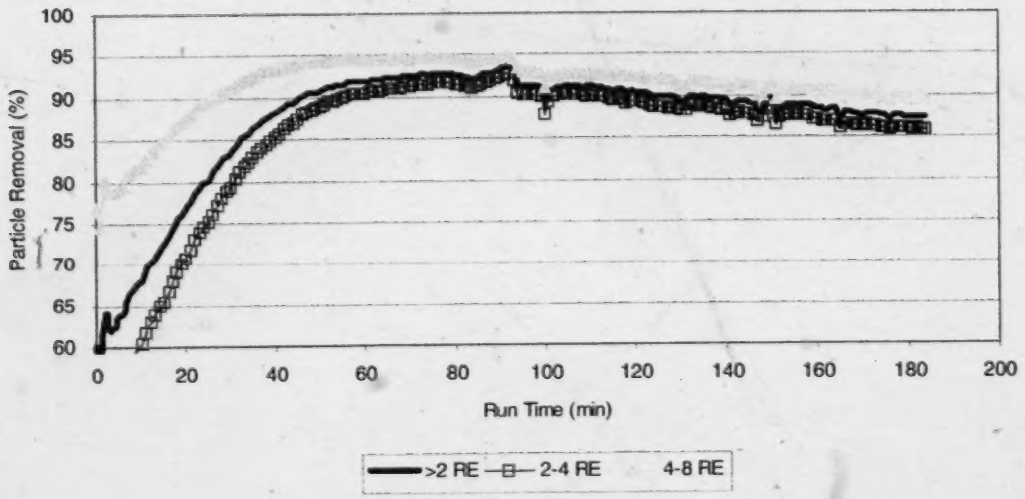
ISO A2 dust influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	782716	518022	229164	29091	4809	1630
Std Dev	56728	28217	24648	3568	524	224
5th	729434	491546	205971	25687	4226	1394
25th	738306	496413	209425	26286	4422	1512
50th	763232	510582	218597	27611	4650	1583
75th	833181	542360	250047	32130	5207	1686
95th	874564	561201	271005	35274	5767	2044
Bin percentage -		66.18	29.28	3.72	0.61	0.21

ISO A2 dust effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	100112	78107	20253	1499	197	57
Std Dev	52979	45973	8081	706	114	31
5th	54515	41619	11279	708	71	19
25th	67384	50742	12520	921	97	32
50th	84920	63422	19645	1318	170	51
75th	107713	78090	24857	2064	275	78
95th	231986	194014	36709	2830	408	113
Bin percentage -		78.02	20.23	1.50	0.20	0.06

MS 10_Removal Efficiency (from 85% ripening to 50 psi pressure drop)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	86.79	84.74	91.14	95.02	96.04	96.47
Std Dev	8.38	9.59	3.81	1.83	2.01	2.00
5th	66.16	59.85	81.61	91.79	92.54	92.61
25th	87.05	86.00	90.06	93.54	94.75	95.39
50th	90.31	88.24	91.95	95.26	96.40	96.72
75th	91.71	90.11	94.19	96.54	97.84	97.99
95th	92.71	91.63	94.64	97.30	98.39	98.77

Turbidity	Influent	Effluent
Median	1.6170	0.2794

Percent particle range removal over time on Run, V10-4, RFFF_MS10_July24



Run, V10-5, RFFF_MS10_July30

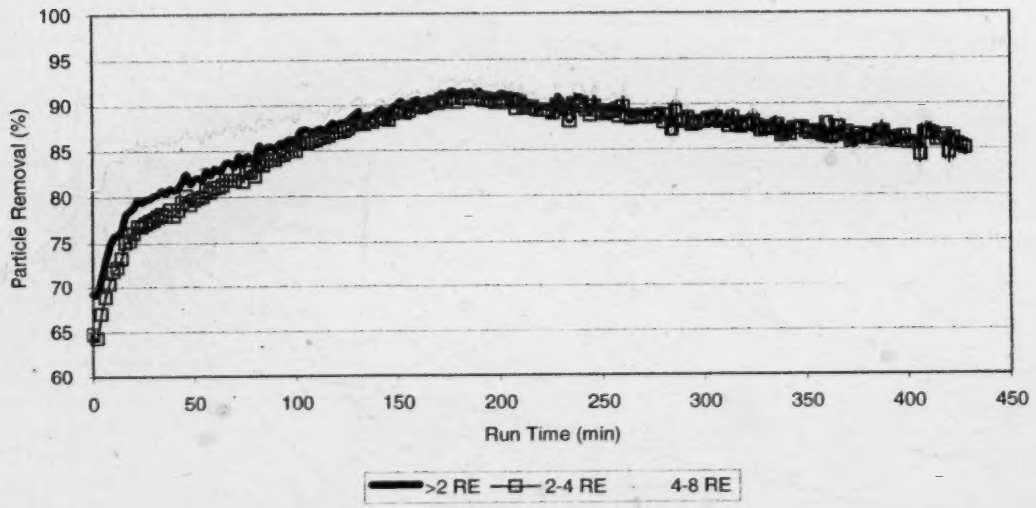
ISO A2 dust influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	417343	304381	99637	11008	1791	526
Std Dev	18351	10397	7264	1843	431	182
5th	390440	289275	89165	8157	1187	254
25th	405413	298033	95002	9531	1438	381
50th	416696	303502	99052	11011	1809	511
75th	427410	310543	103746	12173	2087	648
95th	452427	323993	112159	14037	2535	835
Bin percentage -		72.93	23.87	2.64	0.43	0.13

ISO A2 dust effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	55438	43038	11506	773	95	26
Std Dev	17000	14824	2594	252	40	13
5th	37334	28904	7801	529	49	12
25th	43144	32954	9364	582	63	18
50th	51910	39444	11331	672	87	23
75th	61186	46199	13502	915	117	31
95th	84034	69224	15606	1266	176	51
Bin percentage -		77.63	20.75	1.39	0.17	0.05

Particle Removal on MS 10 (after ripening at 85% to the end w/ 50 psi head increase)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	88.30	87.85	89.03	92.26	93.77	94.20
Std Dev	1.87	1.78	2.47	3.24	3.53	3.63
5th	85.43	84.80	84.74	86.33	87.55	87.10
25th	86.79	86.52	87.68	90.02	91.11	91.76
50th	88.13	87.97	89.29	93.30	94.94	95.51
75th	89.75	89.31	90.94	94.83	96.52	96.92
95th	91.09	90.57	92.38	95.72	97.81	98.13
Median	88.13	87.97	89.29	93.30	94.94	95.51

Turbidity	Influent	Effluent
Median	0.7789	0.1797

Percent particle range removal over time on Run, V10-6, RFFF_MS10_July30



Run, V12-1, RFFF_MS12_June18

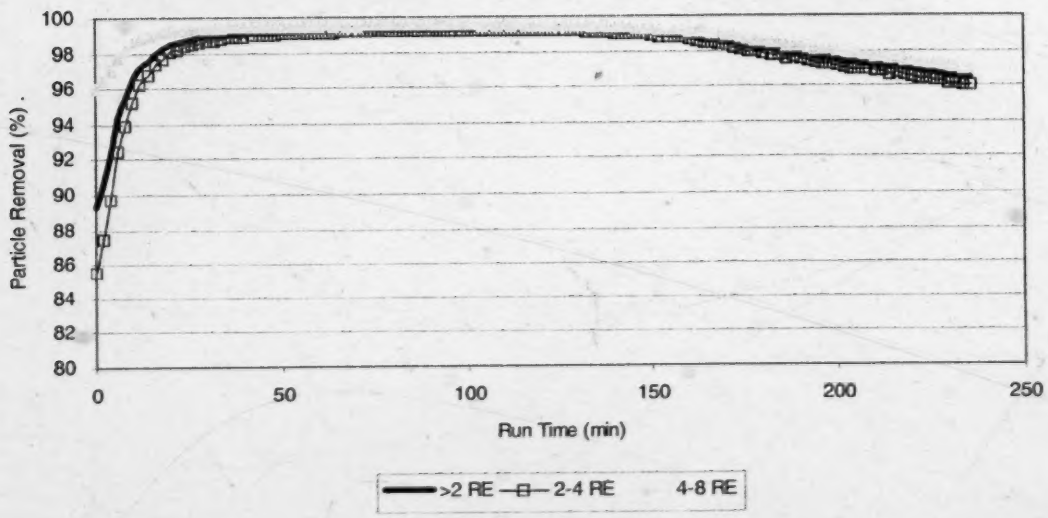
ISO A2 dust influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	760431	486502	236733	30789	4760	1647
Std Dev	31053	14168	14270	2433	451	263
5th	722739	470544	218715	27234	4129	1336
25th	738311	477189	226422	29011	4510	1501
50th	758530	484848	236564	30952	4719	1593
75th	779194	496341	244314	31760	4980	1763
95th	814712	509893	262153	34942	5612	2080
Bin percentage		63.98	31.13	4.05	0.63	0.22

ISO A2 dust effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	12848	9852	2677	264	37	19
Std Dev	11359	9539	2060	204	24	15
5th	4898	3757	976	95	12	5
25th	5359	4041	1113	114	19	10
50th	7778	5767	1483	153	27	15
75th	17486	12725	4030	403	55	21
95th	28224	20313	6840	666	84	45
Bin percentage		76.68	20.83	2.05	0.29	0.14

Particle Removal on MS 13 (after ripening at 90% to the end w/ 60 psi head increase)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	98.30	97.96	98.88	99.16	99.23	98.85
Std Dev	1.61	2.10	0.86	0.63	0.50	0.95
5th	96.41	95.91	97.12	97.90	98.20	97.31
25th	97.69	97.36	98.30	98.83	98.97	98.63
50th	98.96	98.81	99.37	99.49	99.43	99.08
75th	99.29	99.16	99.52	99.61	99.60	99.42
95th	99.35	99.22	99.57	99.68	99.73	99.69
Median	98.96	98.81	99.37	99.49	99.43	99.08

Turbidity	Influent	Effluent
Median	1.3204	0.0799

Percent Particle Range Removal over time on Run, V12-1, RFFF_MS12_June18



Run, V12-2, RFFF_MS12_June 20

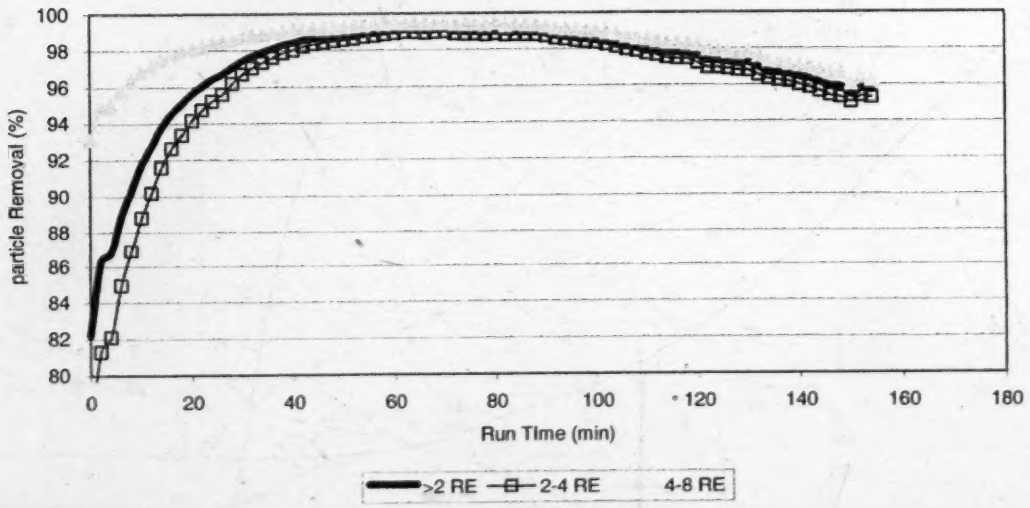
ISO A2 dust influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	777709	497343	242533	31329	4818	1685
Std Dev	38384	20731	15147	2531	597	444
5th	754576	488855	230330	28104	3963	1286
25th	771450	495252	239711	30497	4503	1452
50th	782513	499129	244267	32071	4860	1612
75th	790323	503006	248057	32638	5254	1858
95th	806461	512112	255090	33336	5455	2055
Bin percentage -		63.95	31.19	4.03	0.62	0.22

ISO A2 dust effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	23057	18535	4147	313	42	20
Std Dev	21226	18895	2769	195	19	17
5th	6764	5259	1334	122	18	8
25th	8703	6822	1766	172	26	11
50th	16048	12162	3303	233	40	14
75th	28734	21901	5844	409	54	20
95th	74331	65487	9073	732	79	56
Bin percentage -		80.39	17.99	1.36	0.18	0.09

MS 12_Removal Efficiency (from 90% ripening to 60 psi pressure drop)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	96.94	96.18	98.25	98.99	99.09	98.72
Std Dev	3.15	4.22	1.29	0.65	0.52	1.22
5th	90.07	86.58	96.01	97.69	98.27	96.43
25th	96.43	95.71	97.62	98.73	98.88	98.75
50th	97.93	97.56	98.64	99.26	99.21	99.08
75th	98.89	98.63	99.28	99.46	99.43	99.40
95th	99.13	98.95	99.45	99.62	99.66	99.60
Median	97.79	97.56	98.64	99.26	99.21	99.08

Turbidity	Influent	Effluent
Median	1.3978	0.0799

Percent Particle Range Removal over time on Run, V12-2, RFFF_MS12_June 20



Run, V12-3, RFFF_MS12_June 21

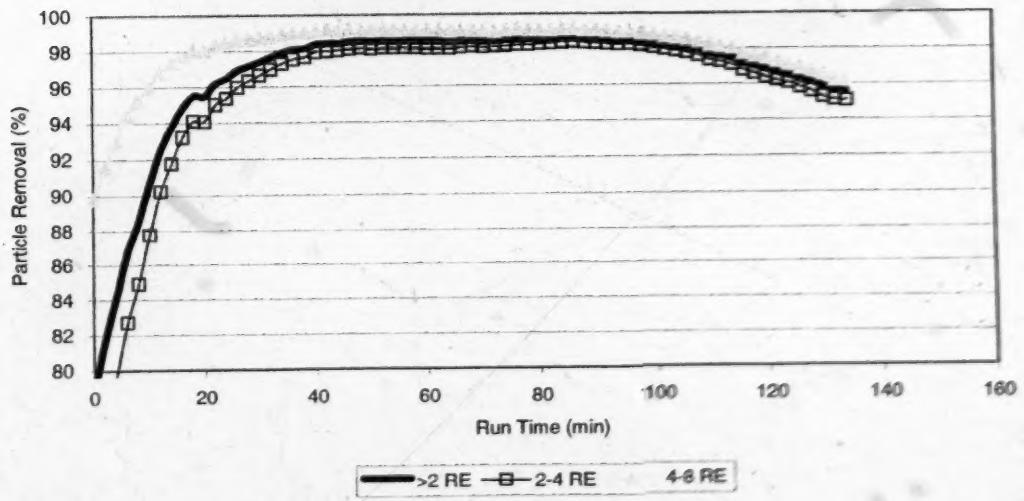
ISO A2 dust influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	754208	486039	233560	29104	4180	1325
Std Dev	38078	17102	17387	3173	558	170
5th	670406	447792	196242	22442	3027	903
25th	744260	483065	227109	27439	3888	1309
50th	759543	488489	237116	30022	4384	1355
75th	776567	495327	244346	31262	4546	1407
95th	799765	506912	254240	32580	4742	1537
Bin percentage -		64.44	30.97	3.86	0.55	0.18

ISO A2 dust effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	25239	20489	4378	309	46	18
Std Dev	25589	22254	3489	186	31	16
5th	10334	7869	1915	157	24	6
25th	11367	9061	2118	200	33	10
50th	14267	11191	2772	226	41	13
75th	27759	21506	5475	369	50	19
95th	84876	73942	10518	666	66	52
Bin percentage -		81.18	17.35	1.22	0.18	0.07

MS 12_Removal Efficiency (from 90% ripening to 60 psi pressure drop)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	96.50	95.64	98.05	98.91	98.80	98.48
Std Dev	3.98	5.12	1.81	0.78	1.24	1.71
5th	87.34	83.49	94.68	97.68	97.97	95.08
25th	96.42	95.77	97.69	98.73	98.84	98.51
50th	98.12	97.73	98.85	99.22	99.09	99.09
75th	98.51	98.15	99.10	99.32	99.25	99.28
95th	98.64	98.37	99.17	99.47	99.44	99.58
Median	98.09	97.73	98.85	99.22	99.09	99.09

Turbidity	Influent	Effluent
Median	1.3204	0.0799

Percent Particle Range Removal over time on Run, V12-3, RFFF_MS12_June 21



Run, T13-1, RFFF_MS13_Aug9

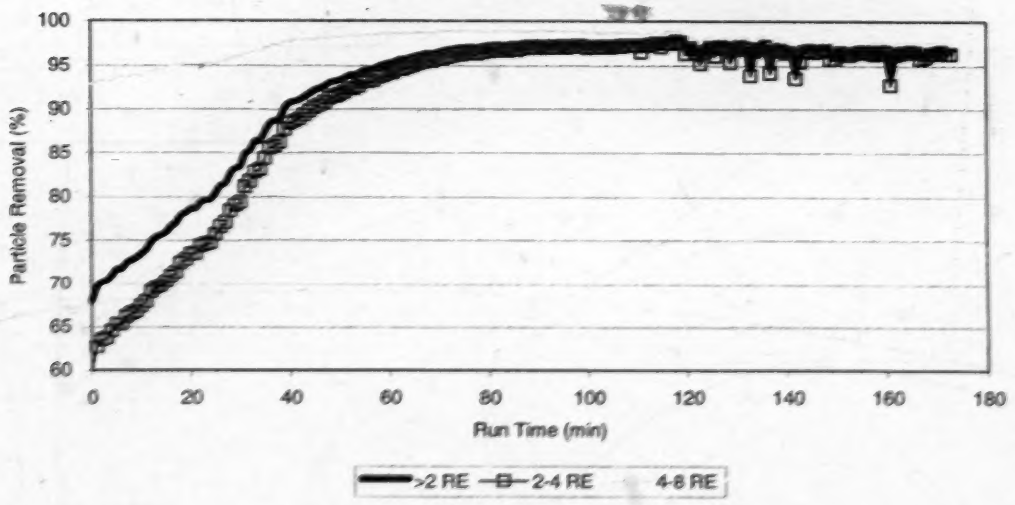
ISO A2 dust influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	560723	413690	131915	12602	1903	612
Std Dev	58166	32787	22256	3151	569	206
5th	450110	348027	92196	8119	1289	436
25th	534555	402104	117282	10090	1460	464
50th	549793	408819	128308	11876	1758	552
75th	600184	434597	148195	14722	2180	695
95th	654345	461735	169209	18573	2955	1001
Bin percentage		73.78	23.53	2.25	0.34	0.11

ISO A2 dust effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	39510	36415	2974	88	14	19
Std Dev	36697	35515	1441	66	12	22
5th	13139	11462	1354	26	2	3
25th	15588	13369	1656	37	5	6
50th	20454	16922	2616	55	11	11
75th	44597	42168	3957	137	20	22
95th	116393	112823	5430	220	34	65
Bin percentage		92.17	7.53	0.22	0.04	0.05

Particle Removal on MS 13 (after ripening at 90% to the end w/ 60 psi head increase)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	96.17	95.39	98.31	99.39	99.45	98.10
Std Dev	2.02	2.58	0.55	0.37	0.33	1.71
5th	91.41	89.32	97.53	98.74	98.94	94.07
25th	95.97	95.24	97.83	99.04	99.23	97.75
50th	96.93	96.44	98.35	99.58	99.49	98.59
75th	97.45	96.97	98.82	99.70	99.72	99.23
95th	97.71	97.27	98.94	99.77	99.89	99.70
Median	96.93	96.44	98.35	99.58	99.49	98.59

Turbidity	Influent	Effluent
Median	1.0368	0.1423

Percent particle range removal over time on MS 13 media, 15GPM initial



Run, T13-5, RFFF_MS13_PRMP_Aug16

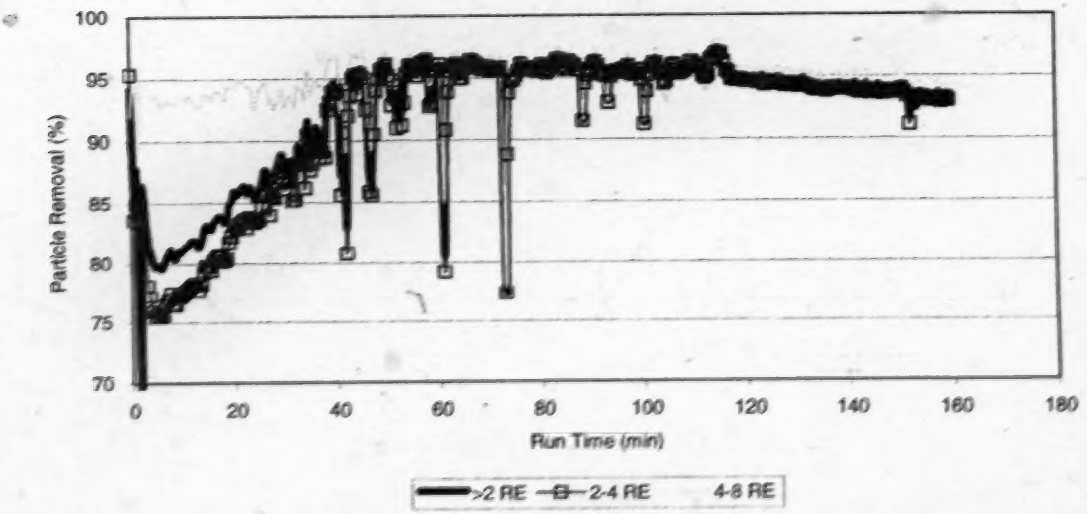
ISO A2 dust influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	202934	151942	45028	4916	807	240
Std Dev	78644	53738	22145	2698	464	135
5th	138897	107044	27508	2342	347	91
25th	148584	113954	30157	3217	513	141
50th	165957	129716	32847	3593	638	217
75th	214062	153322	50524	6396	1015	294
95th	345380	248349	86862	10219	1675	472
Bin percentage		74.87	22.19	2.42	0.40	0.12

ISO A2 dust effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	14232	11847	2154	164	27	40
Std Dev	7211	6583	1094	89	16	60
5th	6347	5117	1025	76	8	7
25th	7536	5962	1416	97	15	12
50th	13371	11190	1711	128	24	20
75th	19359	15611	2462	237	37	36
95th	27584	25322	4333	328	51	201
Bin percentage		83.25	15.13	1.15	0.19	0.28

Particle Removal on MS 13 (after ripening at 85% to the end w/ 60 psi head increase)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	93.44	92.85	95.19	96.43	96.44	80.60
Std Dev	3.69	4.39	1.82	2.11	2.66	27.38
5th	85.45	82.92	92.87	93.77	93.21	7.70
25th	93.78	93.03	94.60	95.90	95.78	80.21
50th	94.83	94.56	95.37	96.78	97.06	89.62
75th	95.76	95.63	96.24	97.52	97.85	95.36
95th	96.44	96.20	97.11	98.45	98.99	97.83
Median	94.83	94.56	95.37	96.78	97.06	89.62

Turbidity	Influent	Effluent
Median	0.7789	0.1547

Percent particle range removal over time on Run, T13-5, RFFF_MS13_PRMP_Aug16



Run, T13-6, RFFF_MS13_Aug28

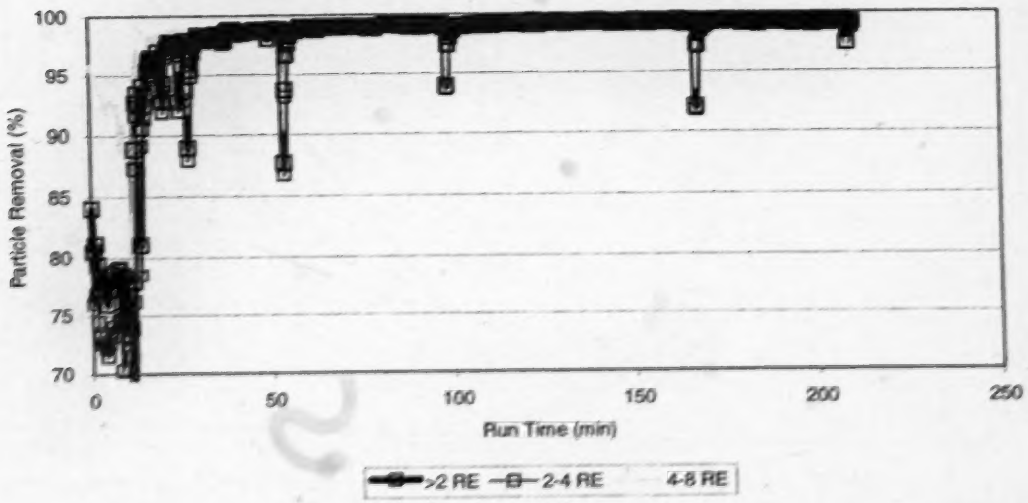
ISO A2 dust influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	155541	120661	30741	3398	575	166
Std Dev	20024	13018	6308	1143	228	90
5th	122109	98997	19912	1894	263	56
25th	139217	110135	25642	2454	397	92
50th	156912	121885	30929	3186	551	148
75th	171597	130913	36025	4334	708	215
95th	186378	140234	40100	5254	936	340
Bin percentage		77.58	19.76	2.18	0.37	0.11

ISO A2 dust effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	4408	3839	505	23	4	36
Std Dev	9430	8422	915	47	14	203
5th	963	767	165	5	0	2
25th	1120	889	201	9	1	4
50th	1392	1130	231	12	2	6
75th	2192	1867	301	17	3	9
95th	34862	31384	2323	74	13	75
Bin percentage		87.08	11.47	0.52	0.10	0.83

Particle Removal on MS 13 (after ripening at 90% point)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	98.69	98.59	98.98	99.46	99.38	93.64
Std Dev	1.38	1.55	0.92	0.82	1.65	10.35
5th	96.41	95.83	97.82	98.68	98.26	83.60
25th	98.82	98.72	99.01	99.43	99.38	93.02
50th	99.10	99.07	99.19	99.61	99.68	95.83
75th	99.23	99.23	99.34	99.76	99.86	97.84
95th	99.36	99.33	99.47	99.87	100.00	99.13
Median	99.10	99.07	99.19	99.61	99.68	95.83

Turbidity	Influent	Effluent
Median	0.8047	0.1049

Percent particle range removal over time on Run, T13-6, RFFF_MS13_Aug28



Run, D12-1, Downflow_MS12_Nov01

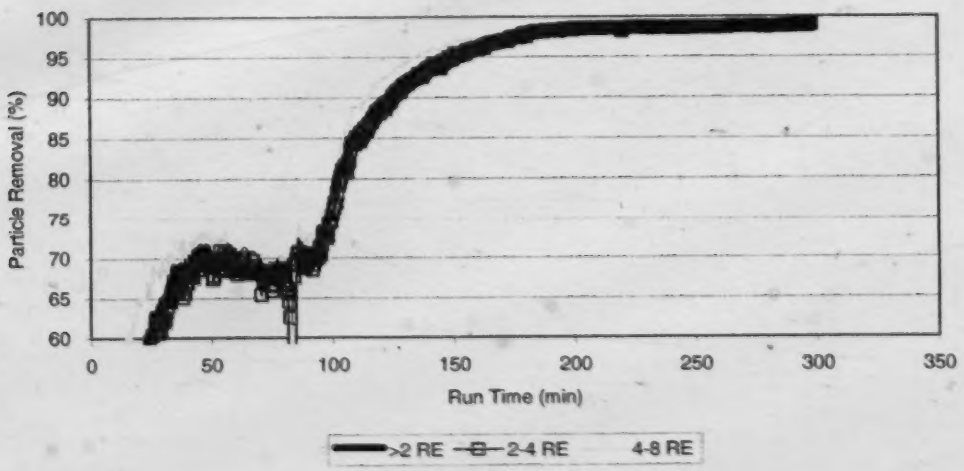
ISO A2 dust influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	155618	122577	29184	3138	537	182
Std Dev	13076	10280	2564	268	56	25
5th	137091	108101	25429	2713	440	141
25th	145823	114865	27315	2964	504	165
50th	153219	120467	28924	3134	540	183
75th	166147	130783	31258	3337	574	199
95th	176528	138965	33303	3552	623	219
Bin [illegible]ntage -		78.77	18.75	2.02	0.34	0.12

ISO A2 dust effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	21660	18008	3600	47	2	3
Std Dev	24115	20154	3964	51	3	7
5th	2038	1599	398	6	0	0
25th	2278	1849	441	10	0	0
50th	7480	6471	991	14	1	1
75th	44745	36496	7884	91	2	2
95th	69909	58916	10469	134	8	8
Bin percentage -		83.14	16.62	0.22	0.01	0.01

Particle Removal on MS 12 (after ripening at 90% to the end)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	97.45	97.28	97.86	99.67	99.87	98.98
Std Dev	2.09	2.33	1.37	0.15	0.29	3.23
5th	92.57	91.83	94.68	99.42	99.53	97.05
25th	96.96	96.71	97.60	99.61	99.81	99.02
50th	98.59	98.55	98.56	99.68	100.00	99.50
75th	98.71	98.70	98.67	99.76	100.00	100.00
95th	98.86	98.86	98.78	99.85	100.00	100.00
Median	98.59	98.55	98.56	99.68	100.00	99.50

Turbidity	Influent	Effluent
Median	1.1915	0.1797

Percent particle range removal over time on Run, D12-1, Downflow_MS12_Nov01



Run, D12-2, Downflow_MS12_Nov02

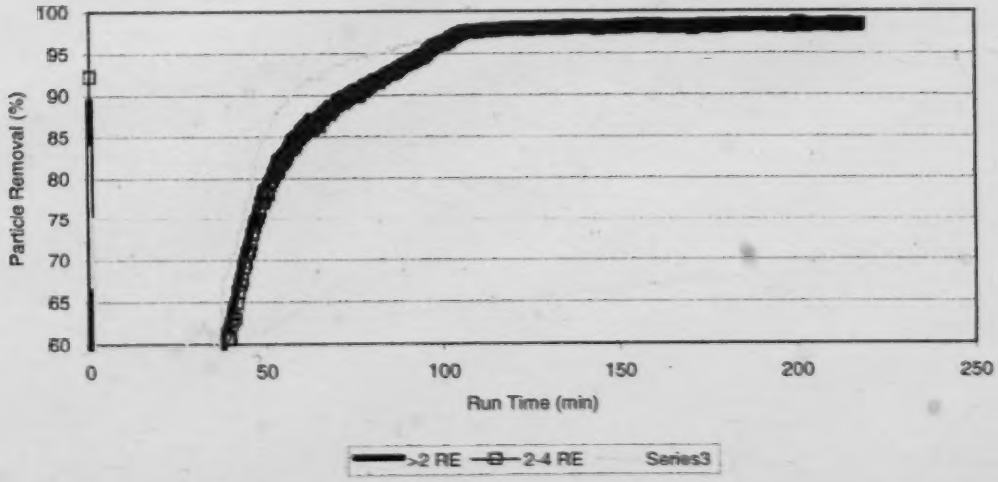
ISO A2 dust influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	236862	188392	43839	3822	612	197
Std Dev	17522	11317	6308	1699	458	160
5th	221801	177739	37823	2983	413	124
25th	230084	183406	40669	3243	485	154
50th	235113	188874	43346	3452	532	173
75th	243863	193171	45647	3809	599	204
95th	251499	199925	51931	5804	984	313
Bin percentage -		79.54	18.51	1.61	0.26	0.08

ISO A2 dust effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	34779	29144	5558	71	2	4
Std Dev	50092	41671	8376	92	4	16
5th	3833	3098	701	17	0	0
25th	4156	3403	745	23	1	0
50th	5796	4842	931	28	1	1
75th	37722	32768	4905	46	3	2
95th	148166	123059	25363	297	7	13
Bin percentage -		83.80	15.98	0.21	0.01	0.01

Particle Removal on MS 12 (after ripening at 90% to the end)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	97.12	96.96	97.60	99.25	99.73	99.01
Std Dev	2.14	2.42	1.15	0.21	0.32	2.97
5th	91.63	90.76	94.77	98.91	99.22	97.13
25th	97.61	97.50	97.85	99.14	99.61	99.28
50th	98.11	98.09	98.10	99.27	99.80	99.54
75th	98.27	98.26	98.19	99.37	100.00	100.00
95th	98.37	98.38	98.34	99.56	100.00	100.00
Median	98.11	98.09	98.10	99.27	99.80	99.54

Turbidity	Influent	Effluent
Median	1.8878	0.1547

Percent particle range removal over time on Run, D12-2, Downflow_MS12_Nov02



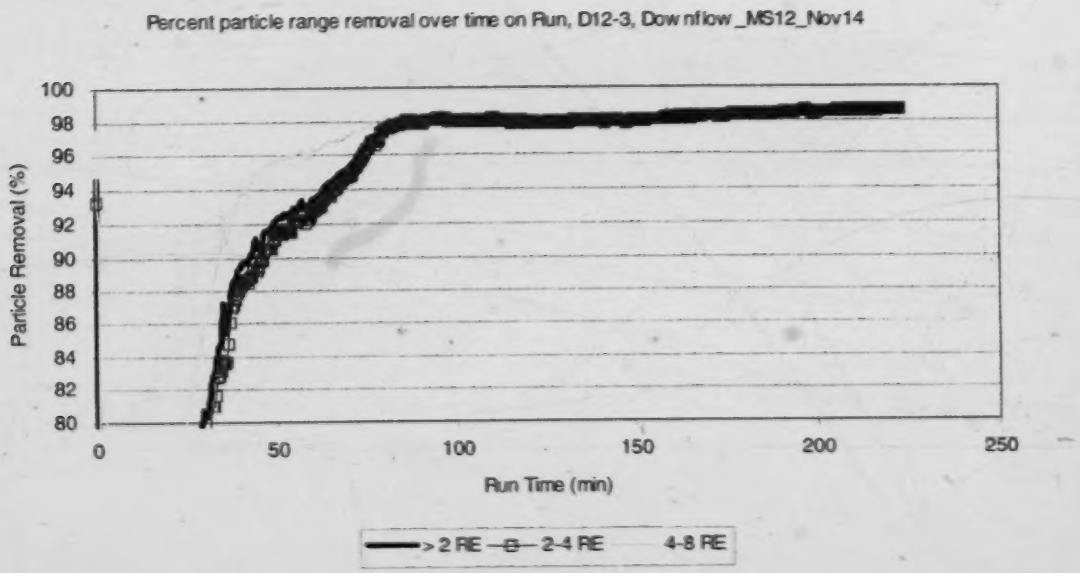
Run, D12-3, Downflow_MS12_Nov14

ISO A2 dust influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	251158	197456	47649	4945	866	241
Std Dev	25671	10746	12603	2846	449	109
5th	232381	186460	41460	3020	445	143
25th	239608	191571	43365	3592	682	192
50th	245817	195465	44698	4519	808	222
75th	254564	200300	46954	5228	930	258
95th	281672	210729	60195	7693	1371	350
Bin percentage -		78.62	18.97	1.97	0.34	0.10

ISO A2 dust effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	21756	18425	3270	49	3	9
Std Dev	38305	31917	6361	85	4	10
5th	3382	2766	591	11	0	1
25th	4269	3559	676	15	0	3
50th	4758	3994	760	19	1	5
75th	16434	14760	1662	26	3	11
95th	106744	90079	16513	229	12	22
Bin percentage -		84.69	15.03	0.23	0.01	0.04

Particle Removal on MS 12 (after ripening at 90% to the end)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	97.32	97.11	98.03	99.55	99.81	96.93
Std Dev	2.03	2.33	0.93	0.20	0.31	4.12
5th	92.43	91.44	95.85	99.19	99.32	91.42
25th	97.96	97.84	98.19	99.45	99.76	96.19
50th	98.14	98.03	98.38	99.59	99.88	98.14
75th	98.39	98.31	98.54	99.69	100.00	98.90
95th	98.61	98.56	98.68	99.78	100.00	99.53
Median	98.14	98.03	98.38	99.59	99.88	98.14

Turbidity	Influent	Effluent
Median	2.0425	0.1547



APPENDIX E

Data Generated in the Filter Challenge and On-Site Experiments, and Detailed Project Chronology

E1. Filter challenge

Comparison with .22 and .45 Gelman membrane in B. Subtilis spore filtration

Sample	A1/A10	A2/A20	A3/A30	A4/A40	A5/A50
expected CFU/mL	200	200	200	200	200
Average counts on .45	98	89	105	106	88
Average counts on .22	96	106	112	97	92

ANOVA: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Average counts on .45	5	486	97.2	72.7
Average counts on .22	5	503	100.6	66.8

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	28.9	1	28.9	0.414337	0.537788	5.317645
Within Groups	558	8	69.75			
Total	586.9	9				

No significant difference

Working stock conc. (spores/mL)= 6.04E+04 Influent conc. (spore/mL)= 19.94

Filter challenge test with B. Subtilis spore on Mil-Spec 12 filter media. Influent port

Interval (min)	10	20	30	40	50	60	70	80	90	100	110	120
Sample Label	A1/A10	A2/A20	A3/A30	A4/A40	A5/A50	A6/A60	A7/A70	A8/A80	A9/A90	A10/A100	A11/A110	A12/A120
Expected conc. (spores/mL)	20	20	20	20	20	20	20	20	20	20	20	20
Average counts (CFU)	19	17	16	16	16	19	15	18	18	17	15	18
Actual conc. (cfu/mL)	1.9E+01	1.7E+01	1.6E+01	1.6E+01	1.6E+01	1.9E+01	1.5E+01	1.8E+01	1.8E+01	1.7E+01	1.5E+01	1.8E+01
Percentage Loss	5.0	15.0	20.0	20.0	20.0	5.0	25.0	10.0	10.0	15.0	25.0	10.0
Log loss	0.02	0.07	0.10	0.10	0.10	0.02	0.12	0.05	0.05	0.07	0.12	0.05
Average Log loss	0.07											

Effluent port

Interval (min)	10	20	30	40	50	60	70	80	90	100	110	120
Sample Label	B1/B10	B2/B20	B3/B30	B4/B40	B5/B50	B6/B60	B7/B70	B8/B80	B9/B90	B10/B100	B11/B110	B12/B120
Expected Removal rate (%)	60	70	80	85	90	90	95	97	98	98	98	99
Sample Volume (mL)	10	10	10	10	20	20	20	40	40	40	50	50
Expected conc. (spores/mL)	8.0E+01	6.0E+01	4.0E+01	3.0E+01	4.0E+01	4.0E+01	2.0E+01	2.4E+01	1.6E+01	1.6E+01	2.0E+01	1.0E+01
Average counts (CFU)	11	21	23	15	21	20	13	11	15	14	10	11
Actual conc. (cfu/mL)	1.1E+00	2.1E+00	2.3E+00	1.5E+00	2.1E+00	2.0E+00	6.5E-01	1.1E+00	7.5E-01	1.4E+00	5.0E-01	1.1E+00
Percentage Loss	94.5	89.5	88.5	92.5	89.5	90.0	96.8	94.5	96.3	93.0	97.5	94.5
Log loss	1.26	0.98	0.94	1.12	0.98	1.00	1.49	1.26	1.43	1.15	1.60	1.26
Average Log loss	1.21											

Filter challenge test with B. Subtilis spore on Mil-Spec 13 filter media. Influent port

Interval (min)	10	20	30	40	50	60	70	80	90	100	110	120
Sample Label	A1/A10	A2/A20	A3/A30	A4/A40	A5/A50	A6/A60	A7/A70	A8/A80	A9/A90	A10/A100	A11/A110	A12/A120
Expected conc. (spores/mL)	20	20	20	20	20	20	20	20	20	20	20	20
Average counts (CFU)	18	20	16	17	19	15	20	17	17	18	15	18
Actual conc. (cfu/mL)	1.8E+01	2.0E+01	1.6E+01	1.7E+01	1.9E+01	1.5E+01	2.0E+01	1.7E+01	1.7E+01	1.8E+01	1.5E+01	1.8E+01
Percentage Loss	10.0	0.0	20.0	15.0	5.0	25.0	0.0	15.0	15.0	10.0	25.0	10.0
Log loss	0.05	0.00	0.10	0.07	0.02	0.12	0.00	0.07	0.07	0.05	0.12	0.05
Average Log loss	0.06											

Effluent port

Interval (min)	10	20	30	40	50	60	70	80	90	100	110	120
Sample Label	B1/B10	B2/B20	B3/B30	B4/B40	B5/B50	B6/B60	B7/B70	B8/B80	B9/B90	B10/B100	B11/B110	B12/B120
Expected Removal rate (%)	60	70	80	85	90	95	96	97	98	99	99	99
Sample Volume (mL)	10	10	10	20	20	20	50	50	50	100	100	100
Expected conc. (spores/mL)	8.0E+01	6.0E+01	4.0E+01	6.0E+01	4.0E+01	2.0E+01	4.0E+01	3. 0E+01	2.0E+01	2.0E+01	2.0E+01	2.0E+01
Average counts (CFU)	17	20	18	17	15	15	18	20	12	12	13	15
Actual conc. (cfu/mL)	1.7E+00	2.0E+00	1.8E+00	8.5E-01	7.5E-01	7.5E-01	3.6E-01	4.0E-01	2.4E-01	1.2E-01	1.3E-01	1.5E-01
Percentage Loss	91.5	90.0	91.0	95.8	96.3	96.3	98.2	98.0	98.8	99.4	99.4	99.3
Log loss	1.07	1.00	1.05	1.37	1.43	1.43	1.74	1.70	1.92	2.22	2.19	2.12
Average Log loss	1.21											

E2. On-site

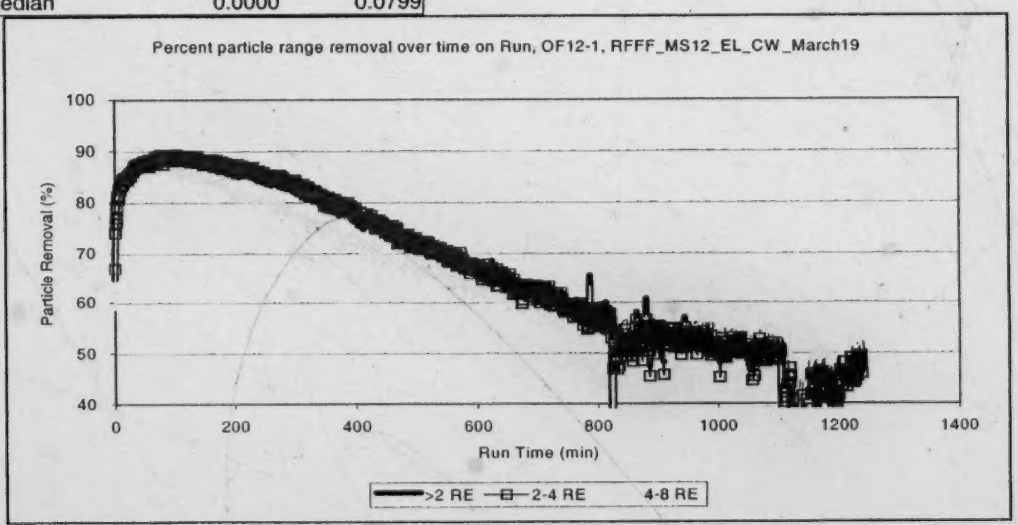
Run, OF12-1, RFFF_MS12_EL_CW_March19

Clarified water influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	11848	8887	2251	538	106	67
Std Dev	1029	804	174	52	17	52
5th	10522	7827	2023	468	86	46
25th	10805	8071	2100	496	96	54
50th	11933	8969	2244	530	104	60
75th	12534	9434	2364	576	113	67
95th	13556	10213	2558	623	127	103
Bin percentage -		75.00	19.00	4.54	0.89	0.57

Clarified water effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	3791	2885	770	133	3	1
Std Dev	1477	1185	256	43	3	3
5th	1585	1181	320	51	0	0
25th	2316	1680	548	104	1	0
50th	4064	3058	848	143	2	0
75th	4974	3836	966	163	4	1
95th	5835	4567	1087	190	8	2
Bin percentage -		76.09	20.31	3.51	0.08	0.02

Particle Removal on MS 12 (from initial run to the end)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	66.80	66.20	64.86	74.49	97.17	99.06
Std Dev	15.02	16.14	13.45	9.68	2.95	3.02
5th	45.07	41.94	47.84	61.41	92.21	96.36
25th	53.74	52.14	53.50	67.12	96.12	98.51
50th	65.90	65.88	62.46	72.51	97.94	100.00
75th	81.73	82.61	76.85	82.03	99.08	100.00
95th	88.16	88.26	87.47	91.70	100.00	100.00
Median	65.90	65.88	62.46	72.51	97.94	100.00

Turbidity	Influent	Effluent
Median	0.0000	0.0799



Run, OF12-2, RFFF_MS12_EL_RW_16GPM_March20

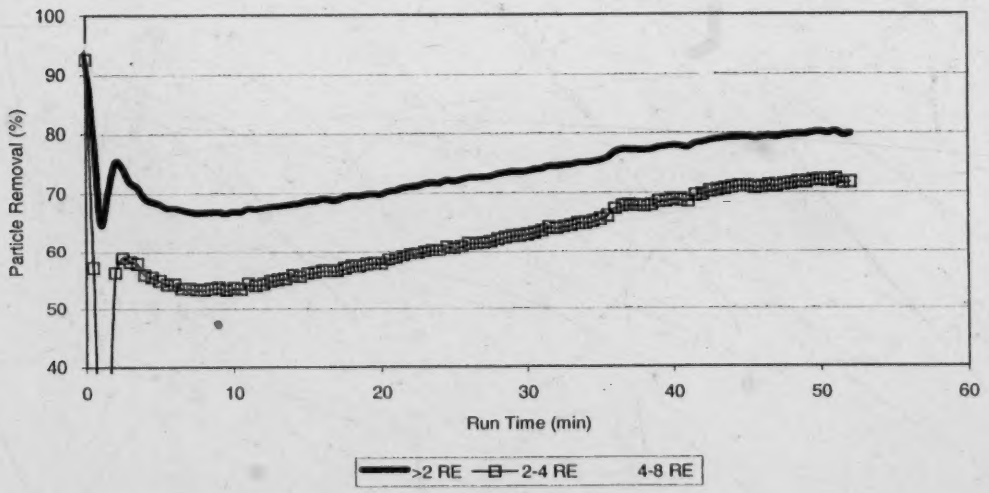
Raw water influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	456549	264645	144299	34708	7962	4935
Std Dev	32903	21772	13634	11498	5546	6372
5th	448645	262793	138303	29165	5761	2715
25th	453390	265139	141084	30587	6242	3154
50th	456010	268909	143830	32723	6890	3782
75th	457535	272097	145525	34233	7513	4190
95th	485161	272852	161104	42995	10193	6530
Bin percentage -		57.97	31.61	7.60	1.74	1.08

Raw water effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	121898	100720	20392	755	24	6
Std Dev	24650	18688	5935	246	12	6
5th	90348	77179	12828	484	15	1
25th	101391	85426	15025	542	18	3
50th	124907	103675	20655	729	21	5
75th	141900	116119	25013	947	26	7
95th	151997	123181	27837	1055	42	15
Bin percentage -		82.63	16.73	0.62	0.02	0.01

Particle Removal on MS 12 (from initial run to the end)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	73.44	61.72	86.01	97.81	99.67	99.86
Std Dev	4.99	9.01	3.58	0.47	0.19	0.15
5th	66.81	53.30	81.07	97.11	99.55	99.76
25th	69.06	56.16	82.83	97.38	99.64	99.82
50th	73.12	61.44	86.25	97.88	99.69	99.88
75th	77.72	68.55	89.35	98.26	99.74	99.93
95th	79.92	71.69	90.71	98.39	99.79	99.97
Median	73.12	61.44	86.25	97.88	99.69	99.88

Turbidity	Influent	Effluent
Median	0.0000	1.1271

Percent particle range removal over time on Run, OF12-2, RFFF_MS12_EL_RW_16GPM_March20



Run, OF13-1, RFFF_MS13_EL_RW_March04_1

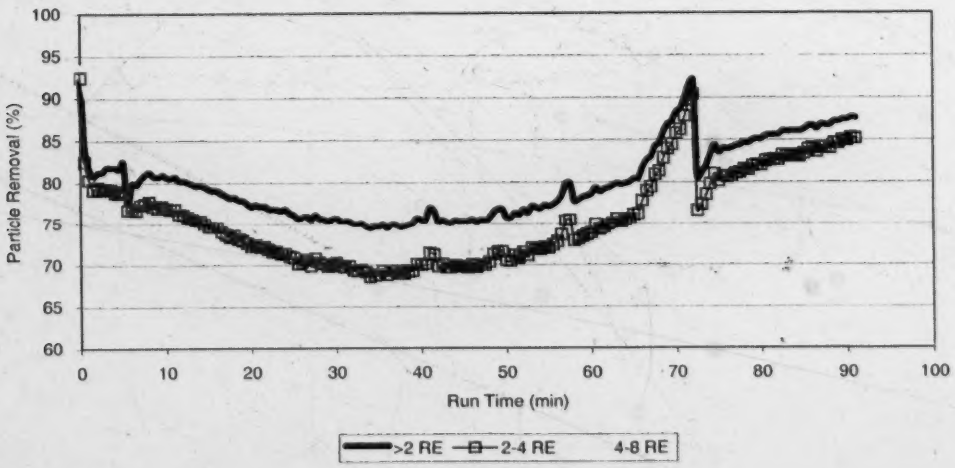
Raw water influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	104811	79108	21234	3519	671	280
Std Dev	4891	2898	1553	414	107	62
5th	100884	77447	19691	3003	517	192
25th	103393	78068	20611	3297	613	251
50th	104280	78672	21093	3509	671	283
75th	104903	79193	21515	3673	715	308
95th	109384	80985	22568	3961	780	350
Bin percentage -		75.48	20.26	3.36	0.64	0.27

Raw water effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	21052	19198	1545	100	17	193
Std Dev	4611	4278	389	50	17	385
5th	12732	11709	920	55	4	12
25th	17573	16191	1275	74	8	30
50th	22019	20003	1646	88	11	75
75th	25205	23185	1799	105	18	162
95th	26162	24079	1937	200	55	876
Bin percentage -		91.19	7.34	0.47	0.08	0.92

Particle Removal on MS 13(from initial run to the end)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	79.91	75.69	92.77	97.25	97.72	42.82
Std Dev	4.36	5.51	1.53	0.97	1.79	93.07
5th	74.87	69.24	91.05	95.09	93.00	-123.89
25th	76.08	70.75	91.58	97.10	97.50	47.36
50th	79.18	74.81	92.33	97.48	98.26	73.15
75th	83.36	80.16	93.90	97.78	98.71	87.43
95th	87.33	84.87	95.37	98.27	99.25	95.06
Median	79.18	74.81	92.33	97.48	98.26	73.15

Turbidity	Influent	Effluent
Median	1.0368	0.7032

Percent particle range removal over time on Run, OF13-1, RFFF_MS13_EL_RW_March04_1



Run, OD13-1, DW_MS13_RW_March10

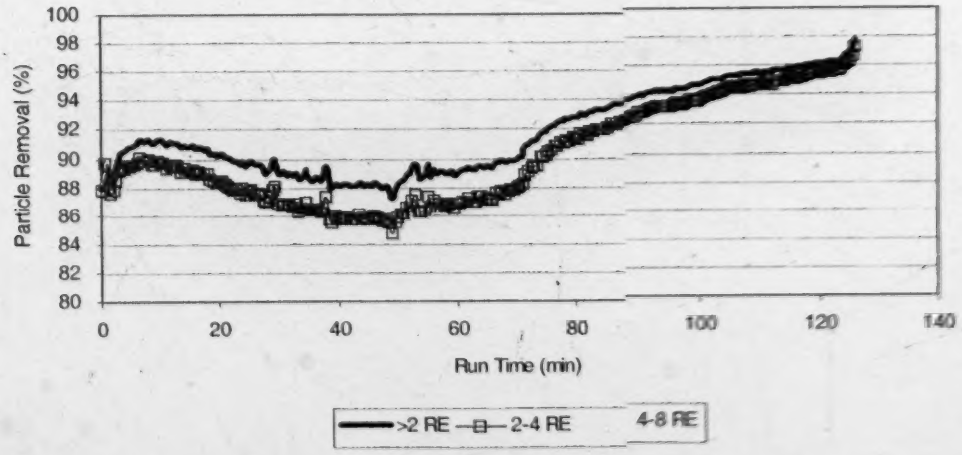
Raw water influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	84300	64004	16836	2770	497	192
Std Dev	2935	1848	864	221	65	35
5th	80349	61733	15573	2420	390	134
25th	82419	63063	16202	2603	445	163
50th	84435	64109	16838	2776	498	199
75th	86150	64895	17469	2964	553	220
95th	87812	66053	17988	3097	590	244
Bin percentage	-	75.92	19.97	3.29	0.59	0.23

Raw water effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	7114	6400	642	59	7	5
Std Dev	2478	2223	291	30	5	5
5th	3134	2808	282	27	2	0
25th	4701	4317	372	39	4	3
50th	7891	6929	714	57	6	4
75th	9273	8371	831	72	9	7
95th	10165	9206	941	96	14	11
Bin percentage	-	89.97	9.02	0.83	0.10	0.07

Particle Removal on MS 13 (from initial run to the end)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	91.62	90.05	96.24	97.90	98.60	97.31
Std Dev	2.79	3.34	1.63	1.00	1.16	2.54
5th	88.13	85.76	94.59	96.78	97.39	94.13
25th	89.16	87.06	95.26	97.55	98.33	96.60
50th	90.91	89.38	95.89	98.02	98.76	97.74
75th	94.30	93.19	97.69	98.51	99.17	98.63
95th	96.12	95.46	98.20	98.95	99.60	100.00
Median	90.91	89.38	95.89	98.02	98.76	97.74

Turbidity	Influent	Effluent
Median	0.9078	0.4539

Percent particle range removal over time on Run, OD13-1, DW_MS13_RW_March10



Run, OD13-2, DW_MS13_EL_CW_March12

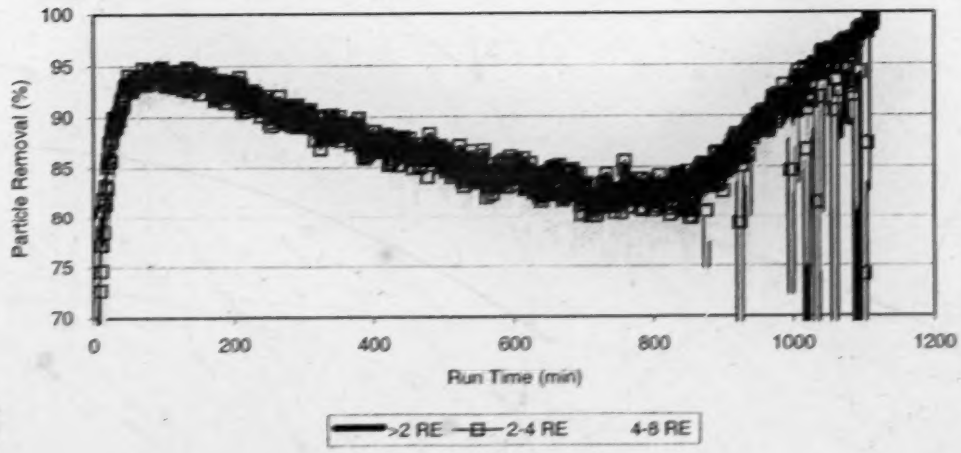
Clarified water influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	3973	3044	761	136	22	10
Std Dev	527	438	80	18	6	5
5th	3280	2484	643	107	13	4
25th	3553	2695	696	122	18	7
50th	3926	2982	766	136	22	9
75th	4323	3309	818	148	25	12
95th	4820	3793	870	163	32	18
Bin percentage -		76.63	19.15	3.41	0.55	0.25

Clarified water effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	530	392	112	14	3	9
Std Dev	665	456	155	35	13	54
5th	208	131	40	4	0	0
25th	351	259	69	7	0	1
50th	505	382	103	10	1	2
75th	613	464	133	13	2	4
95th	682	520	161	23	9	31
Bin percentage -		73.94	21.22	2.62	0.60	1.62

Particle Removal on MS 13 (from initial run to the end)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	86.83	87.29	85.47	89.97	85.77	-34.65
Std Dev	11.68	10.08	14.74	21.21	52.47	837.19
5th	81.21	81.33	77.51	82.23	58.33	-337.81
25th	83.73	83.80	81.95	90.00	88.00	55.14
50th	87.47	87.50	86.47	92.65	95.24	81.82
75th	91.43	91.84	91.39	94.78	100.00	96.97
95th	94.23	94.82	94.59	97.36	100.00	100.00
Median	87.47	87.50	86.47	92.65	95.24	81.82

Turbidity	Influent	Effluent
Median	0.1857	0.0550

Percent particle range removal over time on Run, OD13-2, DW_MS13_EL_CW_March12



Run, OD13-3, DW_MS13_EL_CW_April01

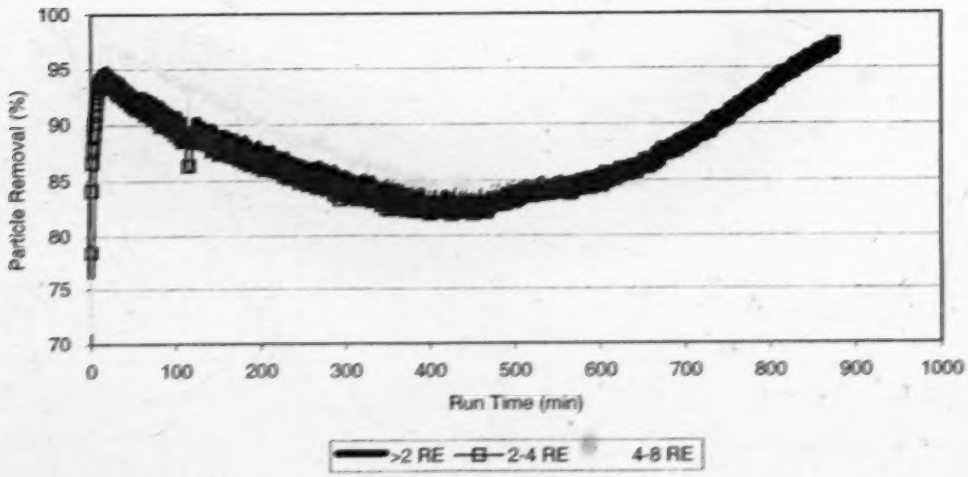
Clarified water influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	51203	41180	7948	1540	325	209
Std Dev	28672	24000	3898	554	140	96
5th	28733	22179	4969	1107	207	126
25th	29535	22967	5095	1154	227	141
50th	34374	27164	5643	1230	254	160
75th	66830	54795	9725	1715	378	249
95th	114356	93407	16773	2828	635	411
Bin percentage -		80.43	15.52	3.01	0.64	0.41

Clarified water effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	5544	4655	853	29	3	4
Std Dev	2232	1835	397	19	6	13
5th	2068	1819	212	12	0	0
25th	3775	3183	547	21	1	1
50th	5297	4432	825	28	2	2
75th	7656	6380	1228	34	3	4
95th	8970	7480	1437	43	6	10
Bin percentage -		83.97	15.38	0.53	0.05	0.07

Particle Removal on MS 13 (from initial run to the end)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	87.99	87.24	88.73	97.97	99.07	97.67
Std Dev	3.83	4.03	4.26	1.49	2.32	6.17
5th	83.55	82.42	83.77	96.80	97.30	92.88
25th	84.65	83.85	84.88	97.56	99.07	97.73
50th	87.00	86.19	87.73	98.09	99.54	98.97
75th	90.86	90.16	92.37	98.64	99.77	99.52
95th	95.13	95.04	96.19	99.13	100.00	100.00
Median	87.00	86.19	87.73	98.09	99.54	98.97

Turbidity	Influent	Effluent
Median	Bad	0.1568

Percent particle range removal over time on Run, OD13-3, DW_MS13_EL_CW_April01



Run, OD13-4, DW_MS13_CW_March 27

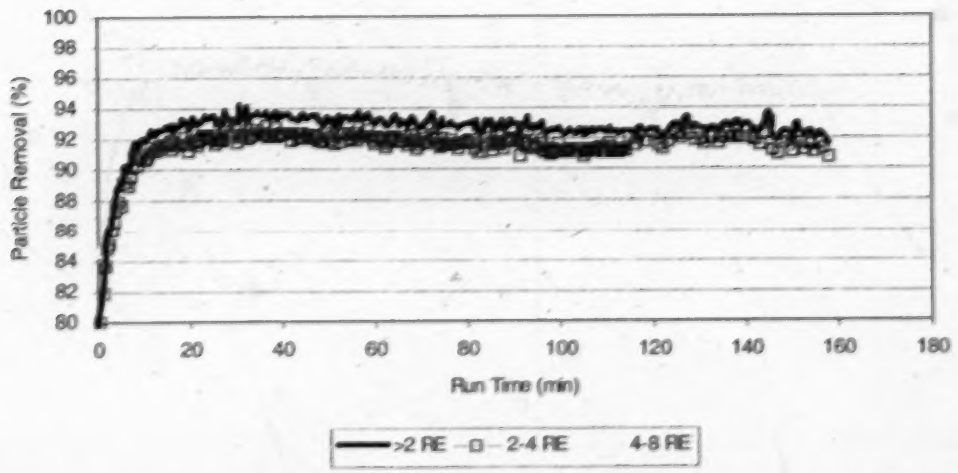
Clarified water influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	16268	12302	3041	666	158	101
Std Dev	1289	898	290	121	38	29
5th	13435	10591	2340	383	72	35
25th	16243	12232	3034	667	151	94
50th	16489	12421	3105	704	166	107
75th	16778	12596	3166	730	179	118
95th	17373	13066	3287	774	202	136
Bin percentage -		75.62	18.69	4.10	0.97	0.62

Clarified water effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	1213	1055	135	8	3	13
Std Dev	299	226	52	8	4	16
5th	994	861	93	2	0	2
25th	1105	979	111	4	1	4
50th	1160	1021	125	6	2	8
75th	1225	1073	140	9	4	13
95th	1579	1319	197	21	11	50
Bin percentage -		86.93	11.11	0.66	0.26	1.04

Percentage particle Removals of different particle size ranges on MS 13 (from initial run to the end)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	92.55	91.43	95.55	98.80	98.01	87.72
Std Dev	1.65	1.64	1.61	1.17	2.34	14.38
5th	90.44	89.38	93.93	96.90	93.38	58.57
25th	92.47	91.28	95.23	98.63	97.65	87.13
50th	92.87	91.76	95.84	99.11	98.73	91.13
75th	93.24	92.10	96.39	99.43	99.39	95.65
95th	93.57	92.44	97.03	99.65	100.00	98.17
Median	92.87	91.76	95.84	99.11	98.73	91.13

Turbidity	Influent	Effluent
Median	0.2026	0.1760

Parcent particle range removal over time on Run, OD13-4, DW_MS13_CW_March 27



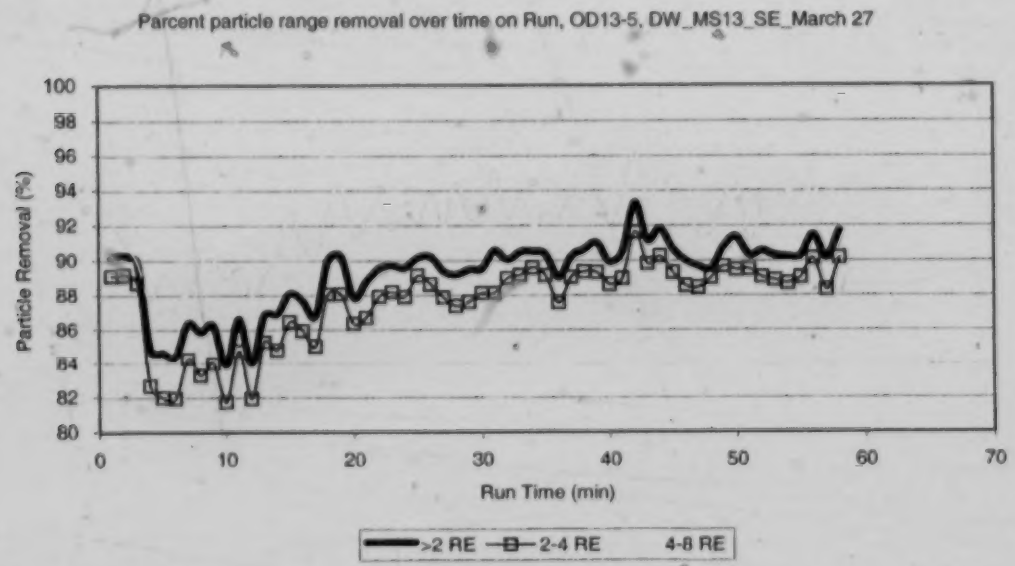
Run, OD13-5, DW_MS13_SE_March 27

Filtrate water influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	4779	3383	965	236	71	66
Std Dev	2820	2056	533	145	46	101
5th	3096	2289	608	121	33	19
25th	3541	2554	728	163	46	31
50th	4101	2920	807	195	57	44
75th	4628	3271	959	261	76	61
95th	8996	6123	1789	475	151	102
Bin percentage		70.79	20.20	4.94	1.48	1.38

Filtrate water effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	523	431	79	6	2	5
Std Dev	315	252	57	5	2	3
5th	295	249	39	1	0	1
25th	332	275	45	2	1	3
50th	399	335	59	5	2	4
75th	560	463	83	9	3	6
95th	1239	1008	202	17	6	10
Bin percentage		82.40	15.05	1.16	0.43	0.96

Percentage particle Removals of different particle size ranges on MS 13 (from initial run to the end)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	89.19	87.59	92.21	97.44	96.82	88.55
Std Dev	2.10	2.40	2.00	1.73	2.38	8.63
5th	84.60	81.97	88.27	94.35	92.94	75.00
25th	88.26	86.51	90.97	96.51	96.05	85.91
50th	89.99	88.49	92.56	97.59	97.10	90.28
75th	90.43	89.11	93.61	98.81	98.02	93.62
95th	91.49	90.09	94.71	99.66	100.00	98.25
Median	89.99	88.49	92.56	97.59	97.10	90.28

Turbidity	Influent	Effluent
Median	0.2000	0.1760



Run, OD13-6, DW_EL_SE_April30

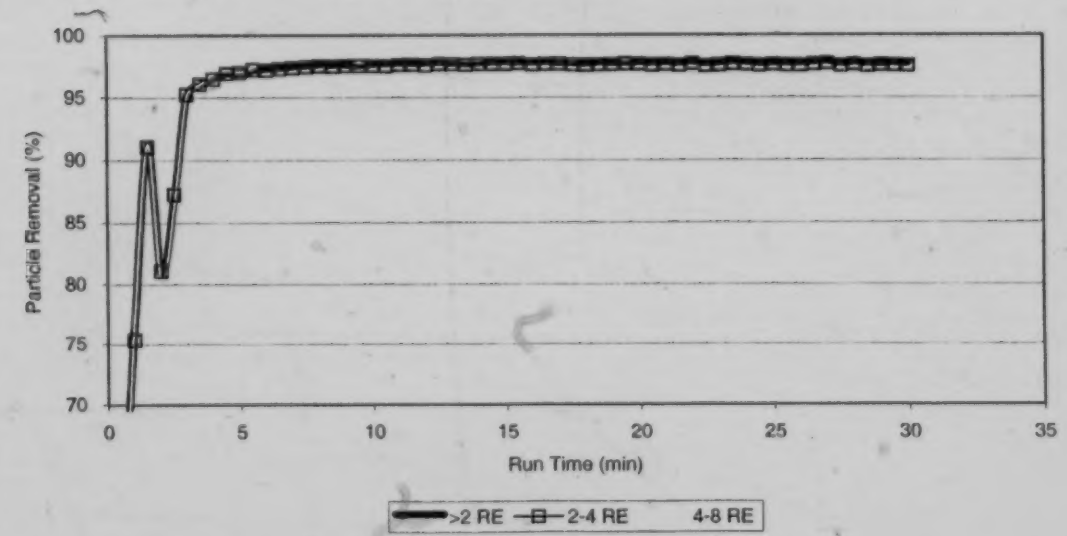
Filtrate water influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	178174	118299	47065	10077	1922	810
Std Dev	39891	10279	12904	9584	4721	2770
5th	165955	114410	42931	7322	761	184
25th	167516	115040	43559	7733	874	214
50th	168321	115394	44036	8010	956	244
75th	171279	116388	45277	8489	1153	343
95th	208227	131145	56266	14965	3927	1924
Bin percentage	-	66.40	26.42	5.66	1.08	0.45

Filtrate water effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	10494	7065	2621	551	117	140
Std Dev	26365	17326	6771	1579	360	427
5th	3602	2680	738	112	16	12
25th	3713	2732	783	125	20	18
50th	3783	2801	827	136	28	31
75th	4170	2977	977	174	35	49
95th	36939	23721	10336	2010	396	476
Bin percentage	-	67.33	24.97	5.25	1.11	1.34

Percentage particle Removals of different particle size ranges on MS 13 (from initial run to the end)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	95.52	94.87	95.94	96.82	96.38	87.33
Std Dev	7.33	10.05	6.97	4.34	2.86	8.17
5th	80.96	81.06	80.21	87.24	88.17	74.52
25th	97.57	97.44	97.84	97.90	96.57	85.65
50th	97.74	97.56	98.11	98.27	97.10	89.00
75th	97.78	97.63	98.21	98.41	97.73	91.71
95th	97.85	97.67	98.30	98.55	98.19	94.40
Median	97.74	97.56	98.11	98.27	97.10	89.00

Turbidity	Influent	Effluent
Median	0.6436	0.1625

Percent particle range removal over time on Run, OD13-6, DW_EL_SE_April30



Run,OD8-1,DW_MS8_EL_RW_March21

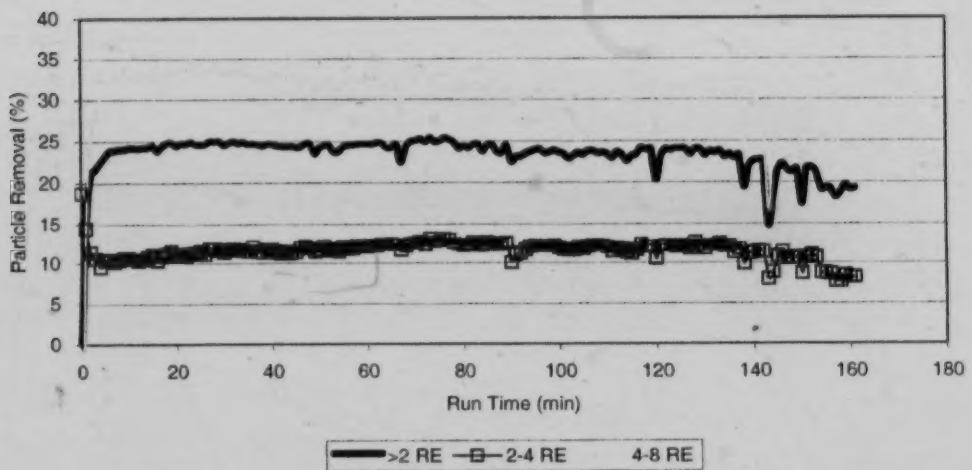
Raw water influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	434724	252092	137097	33537	7612	4386
Std Dev	2486	895	1254	504	154	110
5th	431568	251077	135436	32822	7366	4228
25th	432772	251557	136081	33164	7507	4318
50th	434544	252011	136966	33575	7619	4386
75th	436237	252502	137837	33850	7708	4451
95th	439159	253338	139051	34303	7834	4555
Bin percentage -		57.99	31.54	7.71	1.75	1.01

Raw water effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	333484	223143	95105	13645	1217	374
Std Dev	11628	2971	6457	3106	956	1216
5th	326955	220417	91767	11442	782	149
25th	328316	221321	92473	12284	913	171
50th	330524	222300	93696	13472	1107	219
75th	333010	224384	95266	14092	1256	280
95th	349139	230098	101256	15717	1637	424
Bin percentage -		66.91	28.52	4.09	0.36	0.11

Particle Removal on MS 8 (from initial run to the end)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	23.29	11.48	30.63	59.28	83.96	91.21
Std Dev	2.60	1.25	4.56	9.37	12.65	29.97
5th	19.17	8.68	25.43	51.91	77.81	90.33
25th	23.15	11.07	30.33	58.02	83.35	93.45
50th	24.01	11.68	31.61	59.84	85.58	95.01
75th	24.60	12.18	32.80	63.49	88.19	96.09
95th	25.00	12.65	33.41	66.34	89.97	96.63
Median	24.01	11.68	31.61	59.84	85.58	95.01

Turbidity	Influent	Effluent
Median	3.2094	2.4601

Parcent particle range removal over time on Run,OD8-1,DW_MS8_EL_RW_March21



Run, OD8-2, DW_MS8_EL_RW_April30

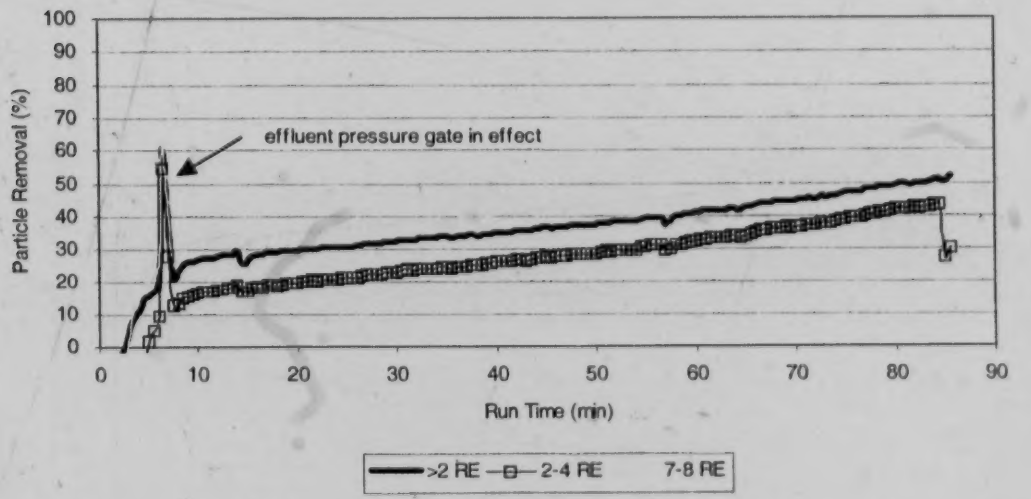
Raw water influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	494775	266938	160739	46098	12227	8773
Std Dev	21180	34797	17532	15448	12495	27918
5th	487680	245997	158351	40948	8839	3975
25th	488670	272697	158842	41720	9247	4271
50th	489502	273527	159394	42319	9627	4497
75th	490691	274802	159849	43229	10070	4708
95th	531886	275844	171597	69795	22434	11173
Bin percentage	-	53.95	32.49	9.32	2.47	1.77

Raw water effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	323950	196314	97597	23500	5116	1423
Std Dev	73614	32053	29703	27381	17973	7542
5th	246086	156777	70762	13852	1678	226
25th	282300	177804	82226	16158	1927	261
50th	314647	198327	93315	18379	2221	294
75th	341382	214995	102915	19829	2392	372
95th	499789	237633	148100	39449	6066	1583
Bin percentage	-	60.60	30.13	7.25	1.58	0.44

Percentage particle Removals of different particle size ranges on MS 8 (from initial run to the end)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	34.84	24.16	38.49	53.79	74.39	91.81
Std Dev	12.09	21.12	22.70	24.75	18.36	4.61
5th	12.94	-3.94	17.29	42.03	63.62	80.87
25th	30.41	20.71	35.70	54.29	76.28	92.13
50th	35.92	26.84	41.52	56.63	77.10	93.34
75th	42.13	33.50	48.07	61.18	79.01	93.93
95th	49.63	41.96	55.24	66.17	81.21	94.46
Median	35.92	26.84	41.52	56.63	77.10	93.34

Turbidity	Influent	Effluent
Median	2.0594	1.0002

Percent particle range removal over time on Run, OD8-2, DW_MS8_EL_RW_April30



Run, OD8-3, DW_MS8_EL_CW_April07

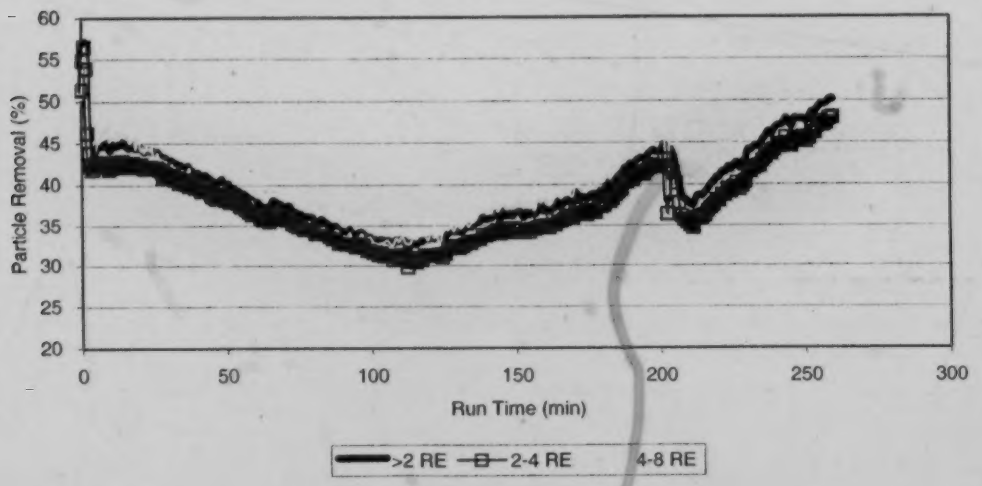
Clarified water influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	244419	179756	51519	9087	2310	1746
Std Dev	6314	3561	2071	494	181	154
5th	231663	172107	47750	8206	1974	1436
25th	239562	177735	49757	8693	2168	1648
50th	247814	181287	52304	9211	2358	1808
75th	249274	182382	53113	9454	2445	1857
95th	250264	183111	53977	9733	2545	1912
Bin percentage		73.54	21.08	3.72	0.95	0.71

Clarified water effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	146025	110904	30489	4073	459	100
Std Dev	12810	9257	3329	496	94	50
5th	120516	93494	23652	3147	336	63
25th	138215	105141	28858	3709	390	76
50th	146447	111004	30938	4150	459	93
75th	154768	117261	32978	4434	516	106
95th	165944	125465	35139	4817	570	166
Bin percentage		75.95	20.88	2.79	0.31	0.07

Particle Removal on MS 8 (from initial run to the end)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	40.29	38.34	40.89	55.17	80.04	94.23
Std Dev	4.62	4.61	5.37	5.00	4.06	2.69
5th	33.19	31.19	33.10	48.05	74.82	91.20
25th	36.59	34.69	36.77	50.93	77.13	93.39
50th	40.23	38.42	40.37	54.42	79.39	94.60
75th	43.97	41.97	44.97	59.65	83.56	95.85
95th	47.77	45.50	50.94	63.12	86.38	96.59
Median	40.23	38.42	40.37	54.42	79.39	94.60

Turbidity	Influent	Effluent
Median	0.7723	0.5051

Percent particle range removal over time on Run, OD8-3, DW_MS8_EL_CW_April07



Run, OD8-4, DW_MS8_EL_RW_SR_April04

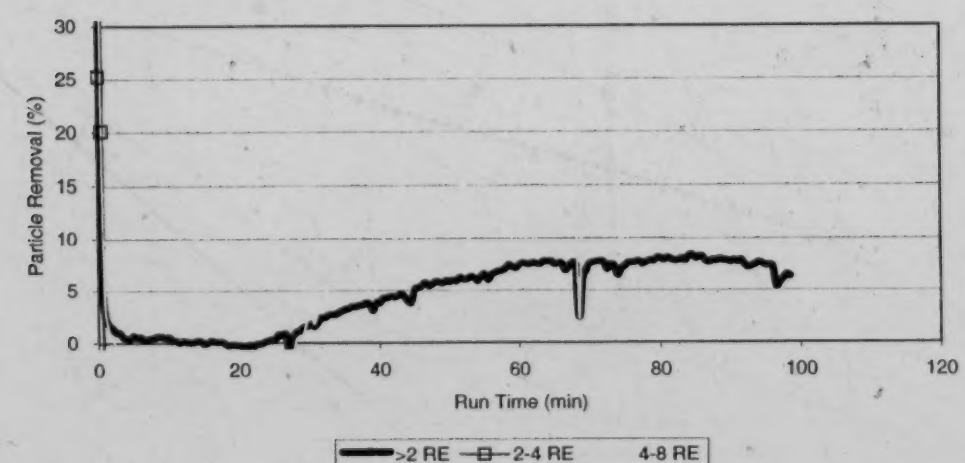
Raw water influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	605348	232478	247903	92597	21351	11020
Std Dev	7273	9783	6272	5470	2370	1983
5th	598827	217904	242618	86532	18374	8582
25th	601590	224697	244617	88528	19193	9095
50th	606192	232455	249153	92802	21148	10666
75th	610020	241794	251680	96432	23307	12846
95th	611610	243922	252669	100129	25048	14075
Bin percentage	-	38.40	40.95	15.30	3.53	1.82

Raw water effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	576875	304978	222512	43210	4688	1487
Std Dev	24543	18421	22217	10522	2604	3348
5th	562505	280915	203024	34346	3641	595
25th	564326	289428	205478	35694	3926	828
50th	571835	314872	214439	37309	4299	1153
75th	595987	317719	246855	52608	4730	1519
95th	600320	318796	252895	59149	5872	1711
Bin percentage		52.87	38.57	7.49	0.81	0.26

Particle Removal on MS 8 (from initial run to the end)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	4.71	-31.24	10.19	53.66	78.06	86.32
Std Dev	4.08	6.52	9.73	9.51	11.00	23.78
5th	-0.09	-36.61	-3.99	39.01	74.43	80.12
25th	1.02	-34.20	-0.91	46.94	76.82	83.23
50th	5.75	-31.42	14.10	57.96	78.85	89.16
75th	7.45	-30.24	18.36	60.21	81.67	93.39
95th	7.91	-26.52	19.41	61.89	83.01	95.72
Median	5.75	-31.42	14.10	57.96	78.85	89.16

Turbidity	Influent	Effluent
Median	8.9326	6.7523

Percent particle range removal over time on Run, OD8-4, DW_MS8_EL_RW_SR_April04



Run, OD8-5, DW_MS8_EL_RW_SR_PO_April 04

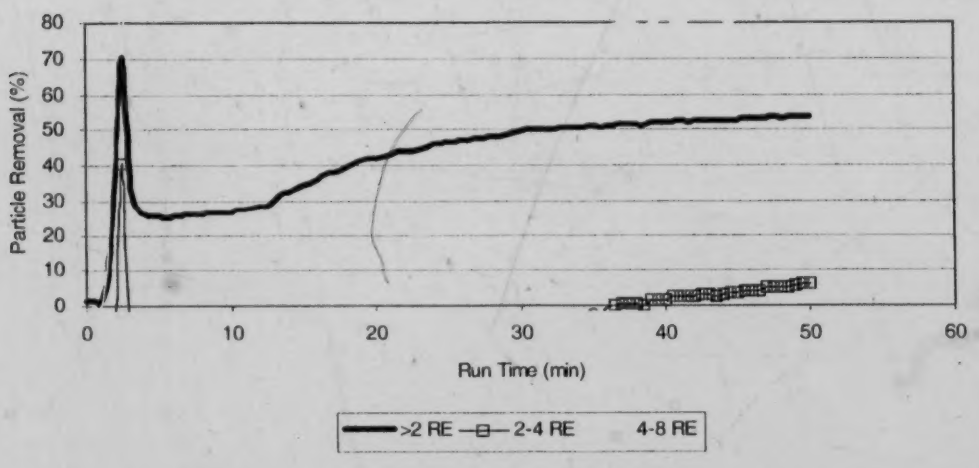
Raw water influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	603388	233832	243961	92958	21750	10887
Std Dev	3510	4301	3745	1459	1481	1828
5th	599000	228239	239066	90655	19620	8523
25th	599906	230001	240276	91529	20297	9160
50th	603048	233000	244080	93470	21739	10620
75th	607088	237996	247995	93950	23140	12616
95th	608794	240715	249487	95036	23957	13525
Bin percentage	-	38.75	40.43	15.41	3.60	1.80

Raw water effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	351111	265295	76565	8248	730	273
Std Dev	76538	35056	40655	7263	544	122
5th	283757	228670	47906	5346	452	112
25th	293799	237430	50110	5459	543	206
50th	322340	256385	58007	5716	624	286
75th	405998	301337	96314	8724	720	318
95th	449459	320605	117619	11292	844	383
Bin percentage		75.56	21.81	2.35	0.21	0.08

Particle Removal on MS 8 (from initial run to the end)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	41.76	-13.70	68.43	91.18	96.66	97.39
Std Dev	12.92	16.74	17.17	7.60	2.22	1.12
5th	25.11	-39.42	50.80	88.02	95.69	95.80
25th	32.23	-31.24	59.61	90.73	96.45	96.60
50th	46.54	-10.04	76.19	93.72	97.07	97.45
75th	51.62	0.45	79.82	94.09	97.65	98.28
95th	53.42	5.17	80.82	94.21	98.08	99.13
Median	46.54	-10.04	76.19	93.72	97.07	97.45

Turbidity	Influent	Effluent
Median	8.9583	4.7407

Percent particle range removal over time on Run, OD8-5, DW_MS8_EL_RW_SR_PO_April 04



Run, OD8-6, DW_MS8_EL_RW_SR_PO_April08

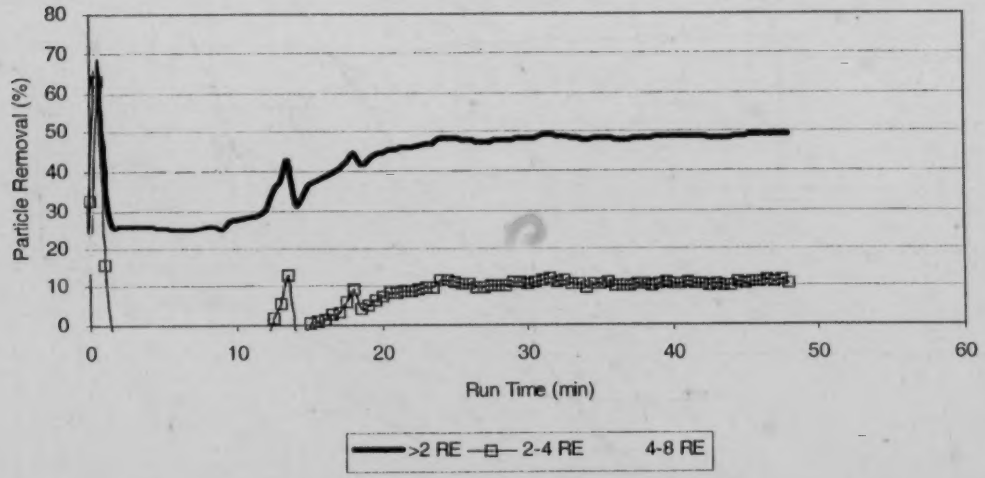
MS 8_clarified water influent						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	558488	255502	210519	67953	16107	8407
Std Dev	21154	3043	14072	6262	1444	975
5th	549195	252442	202234	64060	15733	7554
25th	552578	253942	206022	67812	16069	7730
50th	563298	255413	213736	69460	16275	8262
75th	568098	256430	217329	70143	16561	9374
95th	571747	257557	220231	71049	16879	9617
Bin percentage		45.75	37.69	12.17	2.88	1.51

MS 8_clarified water effluent						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	325521	238680	76658	8790	1007	386
Std Dev	49885	23113	24952	5040	743	451
5th	290155	226454	57024	4930	527	210
25th	293000	228592	58297	5073	565	227
50th	296200	230436	60346	5452	622	245
75th	360058	252454	95292	13060	1369	428
95th	411998	271337	121937	18045	2062	647
Bin percentage		73.32	23.55	2.70	0.31	0.12

Particle Removal on MS 8 (from initial run to the end)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	41.58	6.52	63.00	86.05	92.79	94.62
Std Dev	9.68	9.44	13.86	12.99	12.72	12.98
5th	25.01	-6.44	39.96	72.63	87.55	93.22
25th	33.79	0.27	51.14	79.16	91.65	95.51
50th	47.38	9.91	71.96	92.17	96.19	96.89
75th	48.37	10.79	73.18	92.76	96.49	97.17
95th	49.16	11.72	74.04	93.00	96.72	97.47
Median	47.38	9.91	71.96	92.17	96.19	96.89

Turbidity	Influent	Effluent
Median	4.7366	2.1953

Percent particle range removal over time on Run, OD8-6, DW_MS8_EL_RW_SR_PO_April08



Run, ODN13-1, DW_EL_NMS13_RW_March13

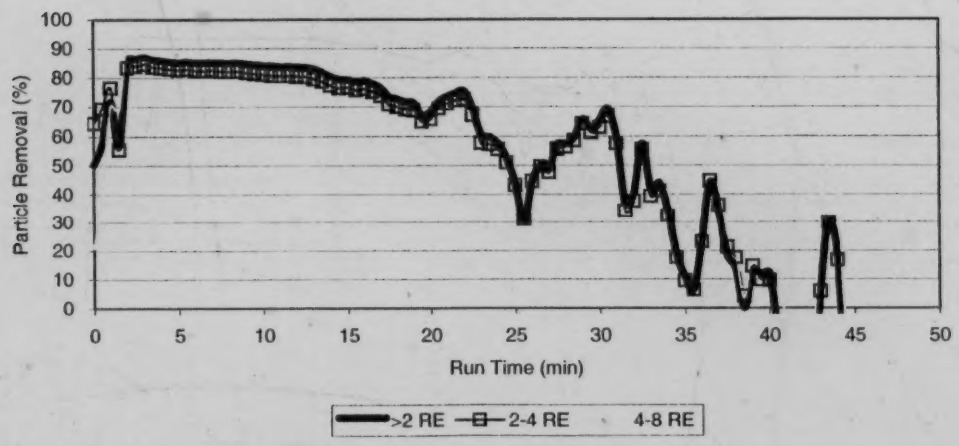
Raw water influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	99084	74451	20349	3402	635	249
Std Dev	19258	14412	4023	695	146	67
5th	101128	76353	20354	3281	559	210
25th	101849	76906	20693	3371	621	233
50th	102698	77301	20943	3498	646	251
75th	103368	77604	21419	3596	674	267
95th	106199	78910	22205	3825	741	306
Bin percentage	-	75.14	20.54	3.43	0.64	0.25

Raw water effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	46939	36692	6504	473	101	3169
Std Dev	36758	27209	6768	277	58	2774
5th	14807	12925	1304	201	40	117
25th	16769	14973	1412	275	73	220
50th	33429	26754	3422	376	90	2623
75th	66648	51352	9120	606	111	5618
95th	130829	99177	22096	1074	206	7938
Bin percentage	-	78.17	13.86	1.01	0.22	6.75

Particle Removal on NMS 13 (from initial run to the end)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	52.53	51.15	66.71	82.59	77.98	-1249.56
Std Dev	35.19	34.37	32.89	20.82	33.38	1189.53
5th	-28.87	-28.99	-8.02	62.42	43.79	-3265.06
25th	34.46	33.69	50.99	79.64	81.11	-2318.29
50th	64.14	64.37	79.48	88.55	86.14	-908.18
75th	82.13	78.87	93.15	92.62	89.69	-82.49
95th	85.57	83.10	93.93	94.60	94.12	60.79
Median	64.14	64.37	79.48	88.55	86.14	-908.18

Turbidity	Influent	Effluent
Median	1.4886	1.0368

Percent particle range removal over time on Run, ODN13-1, DW_EL_NMS13_RW_March13



Run, ODN13-2, DW_NMS13_EL_CW_March17

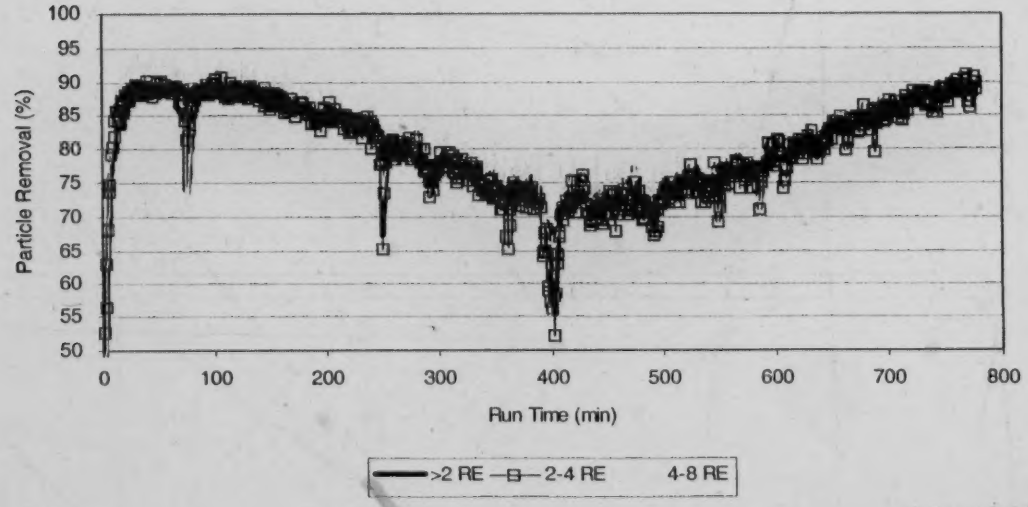
Clarified water influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	3965	3073	735	129	20	8
Std Dev	344	295	50	13	5	5
5th	3546	2721	664	109	13	3
25th	3703	2848	701	119	17	6
50th	3894	3009	731	129	19	8
75th	4176	3249	767	138	23	10
95th	4626	3651	816	151	29	16
Bin percentage -		77.50	18.53	3.25	0.50	0.21

Clarified water effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	769	608	131	9	1	21
Std Dev	326	255	63	7	1	34
5th	419	331	62	3	0	2
25th	541	418	86	6	0	5
50th	730	568	128	8	0	9
75th	952	754	166	11	1	18
95th	1111	894	200	16	3	97
Bin percentage -		79.04	17.02	1.17	0.08	2.69

Particle Removal on NMS 13 (from initial run to the end)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	80.56	80.09	82.14	93.08	96.77	-192.60
Std Dev	7.22	7.55	7.57	4.63	6.85	539.08
5th	70.83	69.44	71.92	87.41	86.64	-1100.00
25th	75.18	74.30	76.98	91.51	95.24	-180.00
50th	81.01	80.82	82.35	93.75	100.00	-20.00
75th	86.65	86.63	88.23	95.62	100.00	42.86
95th	89.13	89.06	92.02	97.69	100.00	80.00
Median	81.01	80.82	82.35	93.75	100.00	-20.00

Turbidity	Influent	Effluent
Median	0.2545	0.1857

Percent particle range removal over time on Run, ODN13-2, DW_NMS13_EL_CW_March17



Run, OD15-1, DW_MS15_EL_CW_March25

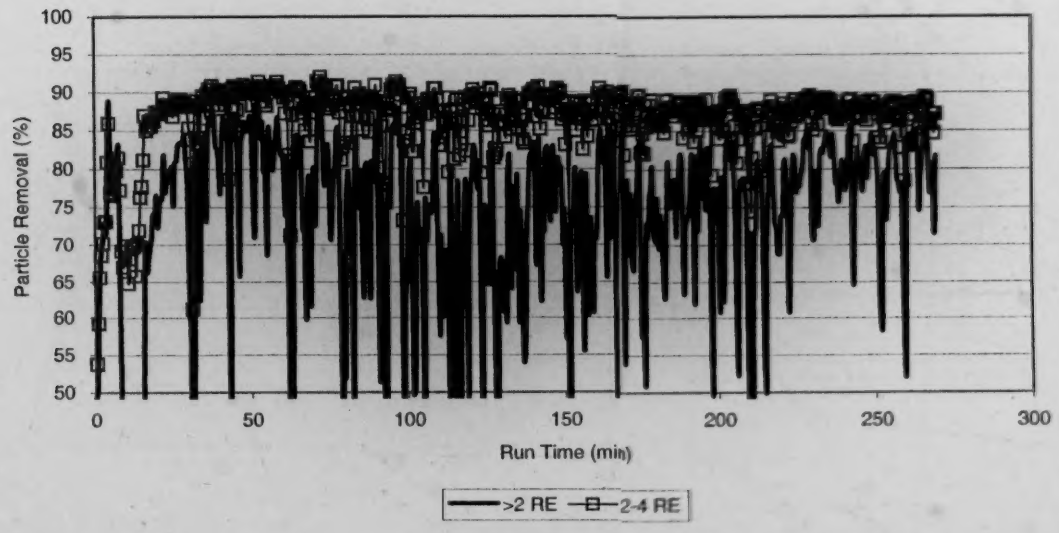
Clarified water influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	17623	12916	3467	845	227	167
Std Dev	3051	1369	942	436	177	160
5th	15693	11750	2976	653	146	85
25th	16820	12559	3210	709	166	106
50th	17118	12759	3291	752	185	124
75th	17430	12940	3398	813	216	157
95th	20493	13909	4318	1318	460	409
Bin percentage -		73.29	19.67	4.80	1.29	0.95

Clarified water effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	5140	1797	613	391	674	1664
Std Dev	4728	947	358	276	594	3223
5th	2447	1205	337	147	193	385
25th	3071	1371	427	220	321	672
50th	3902	1551	522	306	491	1011
75th	5277	1806	655	453	784	1621
95th	10263	3541	1195	920	1638	3329
Bin percentage -		34.97	11.93	7.61	13.11	32.37

Particle Removal on MS 15 (from initial run to the end)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	71.29	86.35	82.41	51.25	-235.80	-939.31
Std Dev	23.71	5.14	7.92	32.47	258.43	1030.85
5th	45.92	76.85	67.49	-7.74	-715.75	-2467.60
25th	69.74	85.83	80.20	40.54	-325.03	-1109.99
50th	77.42	87.76	84.17	60.15	-166.71	-663.94
75th	81.89	88.98	87.14	72.34	-62.31	-417.81
95th	85.58	90.62	90.48	84.22	25.04	-167.48
Median	77.42	87.76	84.17	60.15	-166.71	-663.94

Turbidity	Influent	Effluent
Median	0.2155	0.2295

Percent particle range removal over time on Run, OD15-1, DW_MS15_EL_CW_March25



Run, OD20-1, DW_MS20_EL_CW_March27

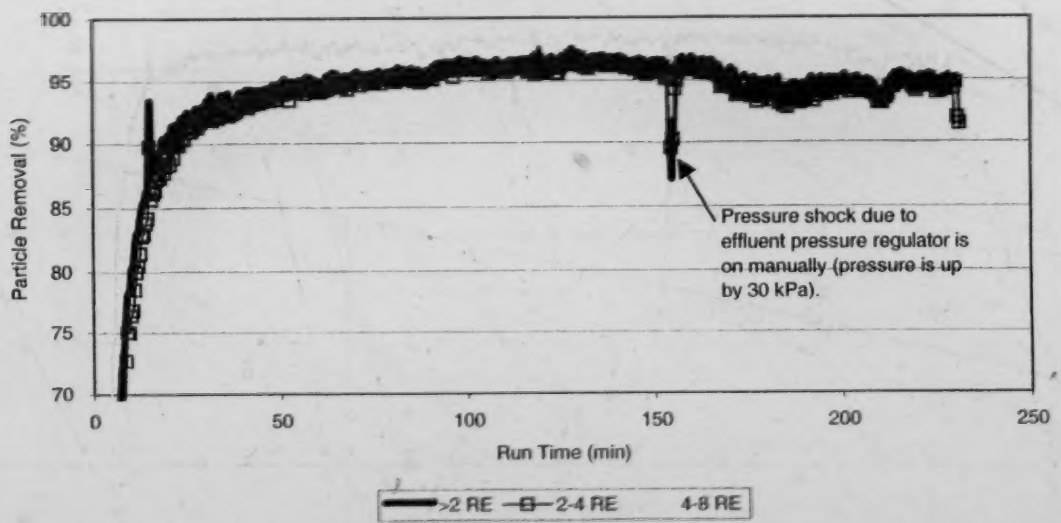
Clarified water influent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	16615	12380	3192	742	182	119
Std Dev	3127	2165	687	232	87	70
5th	10483	7923	1998	471	96	47
25th	14728	11036	2808	634	139	84
50th	17539	13088	3343	754	176	113
75th	18609	13905	3571	821	208	140
95th	20106	14736	3936	969	268	201
Bin percentage		74.51	19.21	4.47	1.09	0.72

Clarified water effluent- particle counts/25 mL						
	>2 Counts	2-4 Counts	4-8 Counts	8-12 Counts	12-15 Counts	15+ Counts
Mean	2426	1973	285	81	42	46
Std Dev	15616	12002	2267	633	363	370
5th	523	433	43	8	2	2
25th	597	508	57	13	5	5
50th	709	606	72	19	8	9
75th	943	801	93	27	12	19
95th	3499	3006	298	73	37	64
Bin percentage		81.31	11.73	3.34	1.73	1.89

Particle Removal on MS 15 (from initial run to the end)						
	>2 Removal	2-4 Removal	4-8 removal	8-12 Removal	12-15 Removal	15+ Removal
Mean	87.34	85.96	92.45	91.31	83.76	75.24
Std Dev	74.39	78.66	54.58	61.33	120.97	152.01
5th	82.99	80.02	91.83	92.14	85.41	63.29
25th	94.38	93.51	97.00	96.44	93.29	85.23
50th	95.21	94.62	97.65	97.30	95.33	91.28
75th	96.27	95.80	98.14	98.03	96.94	94.58
95th	96.80	96.32	98.56	98.69	98.55	97.51
Median	95.21	94.62	97.65	97.30	95.33	91.28

Turbidity	Influent	Effluent
Median	0.2155	0.1760

Percent particle range removal over time on Run, OD20-1, DW_MS20_EL_CW_March27



E3. Detailed Project Chronology

January 2002

- Reviewed report "preliminary investigation of a radial-flow fluidizable filter units for drinking water filtration" from C. W. Baxter.
- Reviewed related publications and books of filtration
- Designed system layout and flow patterns.
- Determined necessary instrument and related piping.
- Measured max flow rate in the Lab B-31 and decide to have alternative water line other than tap water lines to have max 12 GPM.
- Moved old RFFF units and associated equipment from Lab to Lab B31 and cleaned Lab.
- Request price quotes from Cole-Parmer, ClearTech, local steel and welding shops, etc.
- Final proposal discussion and submission to Intergloble and University.

February 2002

- Dissembled old RFFF units and piping assembles to get some useful accessories such as valves, tubes, adapters, etc.
- Took delivery of the RFFF unit from pig-farm waste project and associated equipment at the start of the week.
- Received minimal piping, a steel frame with a base to hold the unit.
- Constructed second ½" water line from water well over ceiling area.
- Constructed a water containment field around the RFFF unit using swimming pool liner.
- Purchased industrial shelve with panels, which were then painted using latex to prevent rotten of woods.
- Purchased tubing and piping to connect various components of the system.
- Pre-installed cutting pipes and fittings on the floor with PVC glue.
- Drilled holes on panels to place the pre-installed system and instruments.
- Connected instruments via RS-485 cable to converter and RS-232 from converter to PC
- Observed several fluidization problems as John Martin tested units for pig farm waste project.

March 2002

- Tested the RFFF units without instrumentation lines or particle injection system.
- Observed leaking from PVC piping and solved.
- New 3-phase 230V wall power plug was placed to deliver best voltage to the new centrifuge pump with a turn on and off switch for better control.
- Observed signal transfer problem and then solved with the help from ClearTech.
- Set up data acquisition system with proper data collection settings.
- Solved PC printing bug with Windows XP operation system.
- Observed several tries of fluidization by John Martin by applying bicycle tire and annular spacers.
- Purchased regulated 12 V power supply for flowmeter from Radio Shack to save money from buying it from Cole-Parmer.
- Purchased UPS from APC, which is recommended by ClearTech to provide stable data transfers.
- Calibrated each of the two turbidity meter with two StablCal solutions, <0.1 and 20 NTU.

April 2002

- Licensed windows and PCX software.
- Repaired 25 (converter) to 9 (PC) pin adapter.
- Installed additional ½" PVC ball valves to control flows going to instruments to prevent undesired high-pressure or contaminated liquid into sensitive devices.
- Installed additional ½" steel plate valves to have extra sample ports for better samplings.
- Mixed two bags of 450 gram ISO A2 fine dust with 200 liters of tap water to stimulate concentrated dirty water.
- Calibrated metering pumps.
- Drew schematics of RFFF units, system layout, flow patterns, etc.
- First time inspected failure of broken inner screen at the bottom of inside cylinder, which may be attributed to the strong flow as fluidization.
- Dissembled RFFF units and fixed inner screen with duck tape and strings.
- Observed bending phenomena of inside cylinder made of PVC schedule 40.
- First system run with flows to instruments and data was recorded in the data sheet in PC.

- Organized raw data from data sheet to preferred MS-Excel layout with the following charts and tables. Charts include Flow rate (GPM) and pressure (psi) over time (min), Influent and effluent turbidity (NTU) over time, Influent and effluent particle injection rate >2 μm (counts/mL) over time, and Percent particle removal (%) over time. Tables include Percentile (5, 25, 50, 75, 95, mean, median, and standard deviation) of influent and effluent particle injection rate over different size ranges, Percentile of turbidity (NTU), and Percentile of particle removal over different size ranges.
- Observed the LMI metering pump can only deliver max. 5,000 counts/mL with liquid concentration of 4.5g/L.
- LMI pump was dissembled to have spared marble balls and diaphragm.
- Replaced LMI pump, which is supposed to provide max. 150-psi flow pressure, still couldn't overcome the mainstream pressure, which is in the range of 15-60 psi.
- No dilution factor is needed into calculation of particle removal because fluidization line can be turned off and filtration line, which has flow meter attached, can be split to both fluidization and filtration lines.
- Received new four-way valve and injection valve for LMI pump, but they didn't work out.
- Received an additional DESAGA metering pump and one Buchler tubing pump from Nick C., which need some repairs and calibrations.
- Fixed DESAGA metering pump with fittings and fitting glue.
- Four system runs on Mil-Spec 10 filter media with combination of pumps to overcome mainstream pressure.

May 2002

- Reviewed pre-treatment literature and drew pre-treatment system layout in AutoCAD.
- Observed other particles other than fine dust in the dust tank and brown deposits under tap water reservoir.
- Flushed dust tank and filled tank with new ISO A2 fine dust and tap water.
- Flushed tap water tank and filled with flesh tap water
- Contacted Pro-western and Zeebest for proper size of tanks which will be used in pre-treatment and increased flow rate.
- Configured and calibrated mixing intensities over specifications of mixing pump, mixing

blade, and dust tank.

- Three more system runs on Mil-Spec 10 filter media were conducted.
- Insufficient backwash was occurred by standard water method.
- Dissembled RFFF units and re-applied duct tape on inner screen and found the filter performance improved, but then decreased over runs.
- Purchased 5 hp air compressor with 27 Gallon container and necessary parts to install air scour system.
- Proved that backwash with both air scour and water can effectively clean glass beads in the RFFR units.
- Observed failure of inner screen which may cause by strong air scour system.
- Being told that there will be tougher and stronger screens designed by John Martin Company along with PVC schedule 80 inner cylinder.
- Observed mushroom-growth-like phenomena by the deposit of glass beads in the center area of lower fluidization chamber (inside cylinder).
- Four system runs on Mil-Spec 12 filter media were conducted.
- Concluded that four factors were required to achieve best filter performance. They are stable particle injection rate, specific height of glass bead in the RFFF unit, complete backwash before next system run, and nature flow declining rate filtration.
- Received an additional 200 Gallon water reservoir, 100 L round-shape water tank, and several bulkheads from Zeebest plastics.
- Contacted Cole-Parmer and ClearTech for a proper pressure transmitter and a signal controlled metering pump.

June 2002

- Connected two 200 Gallon water reservoirs to the system inlet.
- Received re-designed caps and inner and outer screens from John Martin.
- Installed new screens and caps with proper o-rings.
- Found that much better improvement over sealing and assembling on new caps and screens.
- Found that additional outlet on top cap repel air in the RFFF units during fluidization and backwash.

- Observed significant filter performance increase in the first system run on Mil-Spec 12 filter media with 99% particle removal on >2μm.
- Conducted four system runs on Mil-Spec 12 filter media and found that certain range of flow rate and particle injection rate contribute minor effect over particle removal performance.
- Dissembled RFFF units to replace Mil-Spec 12 with Mil-Spec 13 media, which is the smallest glass bead, provided by John Martin Company.
- Specification of new screen was unknown, but was told to be able to retain Mil-Spec 13 media in the RFFF units.
- First system run on Mil-Spec 13 filter media showed very rapid pressure increase and decrease of flow rate over time. Filter performance on particle removal showed a slight less than that of Mil-Spec 12 media. Reasons were unknown.
- Contacted John Martin regarding the above situation.
- Two more system runs on Mil-Spec 13 indicated the same phenomena.
- Dissembled RFFF units to replace Mil-Spec 13 with Mil-Spec 10 filter media.
- Two system runs on Mil-Spec 10 filter media revealed that the substantial filter capability decrease was attributed to the blockage of the screens by Mil-Spec 13 media.
- Confirmed that the blockage was possible because the size of Mil-Spec 13 media is smaller than the new screens.
- Modified backwash method by applying both air scour and water together and hoped this will clean the screens.

July 2002

- Two more system runs on Mil-Spec 10 filter media showed that an increase filter performance over the first two runs on the same media, but indicated incomplete backwash by comparing the pressure chars done by Mil-Spec 12 and Mil-Spec 10.
- Wrote and edited the stage-one interim report
- Modified stage-one report with new layout in the data section
- Received help from Brent to set up system for B. Subtilis spore generation
- Followed instruction from Brent to inoculate test tubes with mother stock, grow spores an Agar, and harvest spores

- Continued inspecting possible passages in the RFFF units
- Additional filter run on Mil-Spec 10 filter media with settings to compare to the best filter performance data with same media and similar settings to further prove the inspection of passage in between inside cylinder and inner screen.

August 2002

- Modified injection point fittings to have abilities to pump either ISO A2 fine dust, polymer addition, B. Subtilis spore, or two of the above into the filtration system
- Purchased new LMI digital metering pump, wide range pressure regulator, 4-20mA converter, and necessary stuffs to set up semi-auto filtration pilot plant.
- Calculated required bottles, solutions, pumping settings, etc. in the next filter challenge test
- Finished updating data result to the stage one report
- Dissembled RFFF units to have the new specific Teflon screens to the Mil-Spec 13 filter media
- Resumed additional tests on Mil-Spec 10, and Mil-Spec 12 filter media with string-wrapped inner screen to prevent passage in between insider cylinder and inner screen

September 2002

- Checked inventories of filter parts in order to ship them to John Martin Company.
- Bacillus Subtilis spore generation was conducted with generous help from Bent and department staffs. Spore preparation, separation, and numeration were instructed and the mother stock concentration is around 2.6×10^9 counts/mL.
- Calculated necessary steps with certain concentration of spore working stock based on main steam flowrate, injection flowrate, expected ripening period and filter performance, etc.
- Observed very less colony counts at the influent than we expected and in few test runs negative filter performance was recorded (i.e. more colony counts at the effluent side than the influent side).
- Discussed with Dr. Smith, Dr. Craik, and department graduate students and concluded four possible ways to solve the strange filter performance, which were discussed in the stage-

two report.

- Background study reveals the system demands of spores such as working stock tank, piping, fittings, connection tubes, instruments, etc.
- First positive spore challenge result based on Mil-Spec 13 media on Teflon screens yielded 1.63 Log removal (equal to 96% spore removal percentile).
- During background spore study, observed significant pressure increase over time without filter media in the upper chamber of RFFF units, which means the only spore and particle removal mechanisms are just system piping and two Teflon screens. This shows that the opening of Teflon screens are blocked by particles or filter media.
- Confirmed that the opening area of Teflon screen is slightly larger than some portion of Mil-Spec 13 filter media with the help of SEM.
- Conducted two sample t-test to compare 0.22 μm and 0.45 μm membranes on colony enumeration and found there is no significant difference.
- SEM photos showed the details of various used and new screens, distribution and size of glass bead media, and B. Subtilis spore and vegetative bacteria shape.

October 2002

- Received inner polyester screen that is claimed to have more opening than PVDF screen and small enough to contain the smallest glass bead (Mil-Spec 13), two caps, and inner cylinder for downflow units
- Discussed issues with David and John regarding the possible failures on the filter units that results in low filter performance (i.e. 6000 counts/mL of particle loading and 400 counts/mL of effluent even after 30 min of typical ripening period.
- Conducted several tests to reveal the problems that cause poor filter performance; included the followings: turned on the ¾" outlet at the top cap to escape the possible trapped air during fluidization; measured glass bead height before and after filtration; desambled filter units to observe possible cracks; replaced o-rings in the units and refilled clean glass beads to the units; recalibrated system instruments
- Replaced suspiciously defective top cap with new cap for the downflow units and found that filter performance is improved over 90% range with long ripening time and significant pressure increase over time. This test was done using polyester inner screen with PVDF

outer screen combo; therefore, less opening on PVDF may attribute the significant pressure build-up and cause a magnitude of break through that results in less filter performance.

- Suggested to have additional acrylic annular, outer cylinder with polyester screen, and caps to complete two independent upflow and downflow units without sharing parts from one another.
- Two tests with Mil-Spec 12 filter media on downflow units were conducted and the results are 85% at mean in terms of >2μm particle removal from initial to the end and 95% of that after ripening period to the end. Observed the same pressure increase over time due to outer PVDF screen in the units.
- Filter media height was observed at four rows of perforated holes below and was suggested by David and John.
- Discussion with John suggested that a split flow at the top filter chamber may ease the pressure increase due to increased flow goes to the annular space instead of cylinder space.
- Filter units tests was stalled and waited for the polyester screen from John Martin.
- Split-flow test on downflow units show some improvement on filter capacity and pressure spike, but it is not comparable with upflow units on the same media. Filter performance curve (>2μm) over time does continue going up even at the max pressure or min flowrate point; therefore, the potentials of downflow units may not be revealed until the outer polyester screen arrived.
- A suggested polyester outer screen to match the inner screen is a key factor that attributes the pressure spike.

November 2002

- Two more downflow units with polyester inner and outer screens were conducted and the results are impressive in terms of particle removal, filter capacities, low pressure increase, etc; however, long ripening time is an issue.
- Discussion with John and David concluded that the initial high pressure drives particles into the filter bed deeply and somehow causes the long ripening phenomena. Background pressure tests reveal that downflow units, in general, have 14 psi more than the upflow units with the same flowrate, filter media, height of inner perforated, etc. Under the same

flowrate 16 GPM, 12 psi and 14 psi for the bypass flow without filter on upflow or downflow units, respectively, and 16 psi and 30 psi with filtration for upflow and downflow units, respectively.

- A recommended inner cylinder with the same perforated height, 26" from 24", similar to the upflow one is needed for the downflow units to compare the real pressure loss issue.
- PVDF screens are likely to be clogged with contaminated particles due to the less opening, screen shape and thickness, etc. As a result, PVDF screens are suitable for less particle waters or used in the final polishing units.
- Ideas of combining downflow units with larger filter media to treat high particle loading waters and upflow units with finer filter media for polishing units have the potentials to utilize both applications (i.e. high initial pressure won't be an issue as size of filter media increases to removal larger particles while low initial pressure on upflow units allow smaller filter media to be fluidized for removing small particles)
- Accompanied with Katey to Dental-Pharmacy Bldg to apply SEM to observe suspicious clogged screen samples cut from three upflow units used in the pig farm project.
- Effluent bypass with additional Tee fitting and gate valve was installed to reduce the initial pressure, which was effective to produce greater particle removal.

December 2002

- B. Subtilis spore concentration was reevaluated and was shown a little decrease from $2.6x10^7$ to $1.8x10^7$.
- Stage-two report based on filter challenge test was drafted.
- Literature reviews to compare data generated from radial filter to conventional filters.

January 2003

- Drafted formal letters to E.L. Smith WTP to have radial filters tested in their pilot plant and permission of applying PcAnywere software for remote access control.
- Draft timeframe of testing radial flow unit in E.L. Smith WTP and request of plumbing works on plant's pipe system.
-

February 2003

- Discussion with two computer engineers to setup an effective and cheap way of controlling multiple devices via Internet connection seems to be possible.
- Estimation of CAD$1500 for designing an interface and a program to do commanding from digital to Analogue controls. Maximum controlled devices are up to 256 and data log record is possible.
- By replacing all the ball valves to solenoids, fully automatic filtration plant can be achieved.
- Received a formal letter from EPCOR that radial flow filter is allowed to be tested in E.L. Smith WTP.
- Destruction of filter system in the school lab, shipping them to E.L. Smith WTP with Gary's help from environmental department, and construction of filter units over the plant has been processed.
- Request of plumbing works have been done and remote access option is still pending.
- System configuration and instrumental calibration has been carried. Sample test run seems well with different water sources and flow directions.

March 2003

- Downflow unit filled with cleaner (more uniform) NMS13 glass media was used to treat raw water and the filter particle removal result was 75% in terms of >2μm size, which was less than that of using MS13 media, 85%.
- Downflow unit filled with NMS13 glass media was tested to treat the plant's clarified water and the particle removal result was still less than the tests using MS13 media.
- Effluent particle count and turbidity meters were observed failure and a complete calibration is needed to bring them back to normal.
- Followed plant's manual particle counter and turbidity procedures to fix the instruments.
- Two complete tests based on a signal factor, flowrate of high, normal, and low, on both upflow and downflow found that lower flowrate will bring the initial pressure down but doesn't affect the particle removal rate. This finding is different than the test done in the school lab with ISO fine dust.
- MS15 and MS20 medias with matched filter screens on downflow unit were tested and the

result found MS20 has better performance based on greater particle removal and longer system run time.

- Difficulty in backwash on downflow unit has been observed.
- Two water tanks with capacity of 400 Gallon were plumed to store filtrate from MS13 downflow unit and then water from which was fed to MS13 downflow unit again to have a sequent filtration. Result showed that 1 log removal of >2μm particles over each filtration.

April 2003

- Instruments of downflow filter system were recorded out of range due to fairly dirty raw water going into the system; therefore, complete instrumental calibrations were performed.
- After successful sequent filtration on MS13 media followed by MS13 media, overnight downflow filter run on MS13 media to treat plant's clarified water was conducted.
- Experienced difficulties to bring downflow filter back to clean status due to incomplete cleanness on outer screen. Several trials to introduce either or both water and air via different flow directions (i.e. outside in and/or inside out from either cylinder or annular space at either top or bottom chamber) to the downflow unit have yielded almost the same result, backwash incompletely. However, introduction of air from bottom inside cylinder out to the annular space can somehow clean the outer screen a little bit.
- Filter polymer injection to the round-shape tank where a mixing intensity of 300 sec^{-1} is provided with piping connection to the downflow unit is set.
- MS8 media on downflow unit was tested to teat plant raw water, which quality is close the spring runoff due to high particle counts and turbidity. The result is poor but useful to compare to the data generated from polymer addition test.
- First run of polymer addition, PERCOL LT-7996, filtration with a dosage of 0.11 mg/L was conducted on downflow unit with MS8 media. Particle removal efficiency was significantly improved from 6% to 47% in terms of >2μm particles.
- Same dosage of 0.11 mg/L of PERCOL polymer was added to the plant's clarified water and the result showed no improvement.
- Jar test in E.L. Smith was carried to seek the optimal polymer dosage on plant's raw water. Poor settling results in no relative evidence of small flocs formation based on turbidity

measurement.

- Sudden On and Off of polymer injection test showed less particle removal efficiency as polymer was added to the plant's clarified water. This may indicate excessive polymers in the water source.
- As E.L. Smith plant has encountered significantly dirty river water due to spring runoff, dosages of Alum, activated carbon, clarified polymer, etc. were added up, which chemical residuals in the clarified water may affect radial filter's functions.
- Alum added clarification has formed flocs, in which most of them was settled as sludge and smaller flocs were drawn to radial filter by centrifuge pump. The extra mixing from the pump has resulted in increasing particle counts due to shear force.
- Sequence filtrations of several combinations of different filter media with either none or little chemical direct filtration seem promising.
- Data log sheet of numerous tests was bund for quick reference.
- Observation of dark discoloration of MS13 media as they were left in the plant for two weeks. 18GPM water flow from annular (outside in) to clean outer screen fails when screen was broken because flow pushes blocked screen inward too much.
- Discussion of adding extra device, which narrow flow into pulse nuzzle in the filter to help cleaning screens, leads to a new area of invention.
- E.L. Smith WTP has encountered the second spring run-off this year when turbidity hits 1,000 NTU and particle counts over 2μm from clarified is 16,000 #/mL.
- The last week tests on plant's raw and clarified water sources with either polymer or Alum or none injection to various filter media sizes have concluded that sequence filtration (stage filtration) can achieve significant particle removals.
- Observed wrong application of applying MS8 or MS5 glass media to treat plant's raw water, which particle counts is out of range and turbidity is high, when filtration run time is significant short.

May 2003

- Alum addition may help forming relatively large flocs, which can be removed by larger filter media, while polymer addition may form smaller flocs, which then can be removed by relatively smaller filter media. As filter media reaches certain size, either Alum or

polymer addition seems no help in terms of particle removal.

- 4-20 mA signals of flowmeter tends to change from time to time; re-calibration the signals is needed.

June and July 2003

- Draft generation.